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THE ENVIRONMENTAL CONTROL OF SEDIMENTARY IRON MINERALS[1]

N. KING HUBER

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[1] Publication authorized by the Director, U. S. Geological Survey.

ABSTRACT

An Eh-pH stability diagram is developed for hematite, magnetite, siderite, pyrite, and iron sulfide that indicates the relative position of their stability fields in a normal sea water system. With the exception of the magnetite-siderite relationship, Eh is much more critical than pH. In general terms, hematite is stable under oxidizing conditions, siderite and magnetite under intermediate to moderately reducing conditions, pyrite under moderate to strongly reducing conditions, and iron sulfide under still stronger reducing conditions. Because of numerous variables involved the relative positions of the stability fields are stressed rather than their limits on the Eh and pH scales. The inclusion of a magnetite field suggests that magnetite should be much more important as a primary or diagenetic mineral in sedimentary rocks than has been commonly recognized. This is in accord with numerous recent suggestions to that effect. The importance of thermodynamic equilibrium is stressed and it is suggested that differences in rates of formation of the various minerals and the persistence of some metastable phases are among the commonest causes of lack of equilibrium.

INTRODUCTION

Equilibrium relationships between various minerals can be treated by the methods of thermodynamics if certain simplifying assumptions are made. The depositional environment of minerals precipitated from natural waters under earth-surface conditions can be considered one of essentially constant temperature and pressure. In many such natural systems the chemical reactions involved may be controlled almost entirely by the hydrogen-ion concentration (pH) and the oxidation potential (Eh) of the environment. By considering the pH and Eh relationships of a postulated environment, the various mineral associations can be predicted and their fields of thermodynamic stability plotted on an Eh-pH diagram comparable to a temperature-pressure diagram.

Suggestions as to the chemical conditions necessary for the formation of various sedimentary iron minerals have been made by Castaño and Garrels (4), and Krumbein and Garrels (17) have presented an Eh-pH stability diagram for hematite, siderite, and pyrite in a normal sea water system. Further theoretical considerations and some experimental verifications were given by Huber and Garrels (15). These studies were based on data for compounds that approximate the compositions of hematite (actually $Fe(OH)_3$ was used), siderite, and pyrite (actually FeS was used). Magnetite was not considered, nor, except briefly by Castaño and Garrels, were the iron silicates.

Recently, the writer's attention has been called to the work of Pourbaix (22) who has calculated Eh-pH stability fields for hematite, magnetite, and elemental iron in a study of the "corrosion domains" of iron. In a recent continuation of this work Deltombe and Pourbaix (7) presented a diagram indicating the Eh-pH relationships between hematite, magnetite, siderite, and elemental iron. The methods used by Pourbaix and his co-workers are based upon potential equations derived from free energy data allowing application to nearly all mineral species for which free energy data are available. Utilizing the methods of Pourbaix, the present study expands

the previous work and presents an Eh-pH stability diagram for hematite, magnetite, siderite, pyrite, and iron sulfide (FeS).

Acknowledgments.—This paper covers some of the theoretical aspects of a larger study of iron-formation sedimentation that is part of a regional study of the Lake Superior iron ranges being made by the U. S. Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation. Additional assistance for the work described in this paper was provided by the S. F. Emmons Memorial Fellowship, which the writer held while at Northwestern University during the academic year 1953–54. H. L. James of the U. S. Geological Survey, A. L. Howland of Northwestern University, and R. M. Garrels of Harvard University made many valuable suggestions during the development of the study.

DETERMINATION OF MINERAL EQUILIBRIUM RELATIONS

Magnetite-Hematite Equilibrium.—The boundary between the magnetite and hematite stability fields is established by determination of Eh and pH values at which magnetite and hematite can coexist in thermodynamic equilibrium at 25° C.

The relation between magnetite and hematite in an aqueous system can be written as

$$3Fe_2O_3 + 2H^+ + 2e^- = 2Fe_3O_4 + H_2O;$$

or

$$3Fe_2O_3 - 2Fe_3O_4 - H_2O + 2H^+ + 2e^- = 0 \qquad (1)$$

with all symbols collected on the same side of the equation and where e^- represents an electron. If this is considered a reaction of the type

$$aA + bB + cH_2O + mH^+ + ne^- = 0 \qquad (2)$$

(22, p. 9) then the standard potential for the reaction is given by

$$E^\circ = \frac{a\Delta F_A^\circ + b\Delta F_B^\circ + c\Delta F^\circ_{H_2O} + m\Delta F^\circ_{H^+}}{23{,}060n} \qquad (3)$$

(22, p. 9) where ΔF_X° is the standard free energy ("standard chemical potential" of Pourbaix) for each of the components in the reaction.

The potential, Eh (E of Pourbaix), for such a reaction is given by

$$Eh = E^\circ + \frac{RT}{n\mathfrak{F}} \ln Q. \qquad (4)$$

In the above equation E° is the standard potential for the reaction; R, the gas constant, equals 8.314 joules/degree; $\mathfrak{F}$, the Faraday, equals 96,496 coulombs; T is the absolute temperature; and $Q = (a_A)^a(a_B)^b(a_{H_2O})^c(a_{H^+})^m$ or the product of the activities (a_X, expressed in moles/liter) of the various components raised to the power of their coefficients. After substituting

the proper constants at 25° C, changing to logarithms of base ten, and replacing $-\log a_{H^+}$ with pH, the equation becomes

$$Eh = E^\circ - \frac{0.0591m}{n} pH + \frac{0.0591}{n} [a \log a_A + b \log a_B] \quad (5)$$

the activity of H_2O being taken as one.

Values for the standard free energies of various components used in the calculation of the stability fields are listed in Table 1.

For the magnetite-hematite relationship given in equation (1), a value for E° may be obtained from equation (3) by proper substitution of standard free energies from Table 1. For this system, then, equation (5) becomes

$$Eh = 0.221 - 0.0591\ pH \quad (6)$$

the activity of all solids being taken as unity. Equation (6) represents the locus of points lying on the hematite-magnetite boundary (i.e., hematite and magnetite coexisting in thermodynamic equilibrium at 25° C). If a series of pH values is assumed, corresponding Eh values can be calculated and the hematite magnetite boundary plotted on an Eh-pH diagram.

TABLE 1

STANDARD FREE ENERGY AT 25° C (CALORIES PER MOLE)

H^+ aq.	0	$FeCO_3$	−161,060
H_2O	− 56,690	FeS	− 23,320
Fe^{++} aq.	− 20,300	FeS_2	− 39,840
		$S^=$ aq.	+ 22,100
Fe_2O_3	−177,100	$CO_3^=$ aq.	−126,220
Fe_3O_4	−242,400	$SO_4^=$ aq.	−177,340

Values from Latimer (18).

Carbonate Equilibria.—The activity product constant for siderite is given by Latimer (18, p. 222) as

$$a_{Fe^{++}} a_{CO_3^=} = 10^{-10.68}. \quad (7)$$

It is apparent from the above relation that the solubility of siderite (and thermodynamic stability) is dependent upon the activity of carbonate ions in the aqueous system under consideration. The activity of carbonate ions in sea water is dependent upon the pH of the system through the carbon dioxide equilibria

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^= + 2H^+. \quad (8)$$

It is also dependent to a lesser degree upon the salinity and chlorinity of the system. Sverdrup, Johnson, and Fleming (29, p. 195–202) present a detailed discussion of the distribution of the CO_2 components in sea water with methods for calculating the concentrations of the various components. The carbonate ion concentrations used in this study for the determination

of siderite stability are taken from data supplied by Sverdrup et al. Garrels and Dreyer (11) also discuss the relations between concentrations, activities, and equilibrium constants for the carbon dioxide system in regard to the determination of carbonate ion activity in sea water.

Magnetite-Siderite Equilibrium.—The relation between magnetite, siderite, and carbonate ion activity can be written as

$$Fe_3O_4 - 3FeCO_3 - 4H_2O + 3CO_3^{=} + 8H^+ + 2e^- = 0, \quad (9)$$

where the equilibrium potential for the reaction is

$$Eh = 1.93 - 0.236\,pH + 0.0887 \log a_{CO_3^{=}} \quad (10)$$

as calculated by the methods of Pourbaix. By substitution in equation (10) of the activity of carbonate ions at various pH values, a series of Eh values can be calculated for magnetite-siderite equilibrium and the boundary between the respective fields can be defined.

Hematite-Siderite Equilibrium.—The equilibrium relations between hematite and siderite can be written as

$$Fe_2O_3 - 2FeCO_3 - 3H_2O + 2CO_3^{=} + 6H^+ + 2e^- = 0 \quad (11)$$

$$Eh = 1.36 - 0.177pH + 0.0591 \log a_{CO_3^{=}}. \quad (12)$$

As noted in the previous section, at any assumed pH, the carbonate ion activity is fixed and the equilibrium Eh can be calculated from equation (12). A series of such calculations will serve to define the boundary between the hematite and siderite stability fields.

Sulfide Equilibria.—The total sulfur content of normal sea water is approximately $10^{-1.5}$ moles/liter (29, p. 173) and can be considered to be distributed among $S^=$, HS^-, H_2S, and $SO_4^=$, according to the dissociation constants of H_2S and H_2SO_4. Other sulfur species are negligible for the purposes of this study. The activity of the sulfide ion must also be in equilibrium with the sulfate ion activity through the equations

$$SO_4^= - S^= - 4H_2O + 8H^+ + 8e^- = 0, \quad (13)$$

$$Eh = 0.148 - 0.0591pH + 0.0074 \log \frac{a_{SO_4^=}}{a_{S^=}}. \quad (14)$$

With these relations the sulfide ion concentration can be calculated for any assumed Eh and pH values.

Magnetite-Pyrite Equilibrium.—The equilibrium relationship between magnetite and pyrite is given by

$$3FeS_2 + 4H_2O - Fe_3O_4 - 6S^= - 8H^+ + 4e^- = 0, \quad (15)$$

$$Eh = -2.56 + 0.118pH - 0.0887 \log a_{S^=}. \quad (16)$$

However, because a_{S^-} is fixed for any given Eh and pH conditions, a pair of subsidiary equations are necessary for making the equilibrium calculations:

$$Fe_3O_4 - 3Fe^{++} - 4H_2O + 8H^+ + 2e^- = 0 \quad (17)$$

$$Eh = 0.98 - 0.236pH - 0.0887 \log a_{Fe^{++}} \quad (18)$$

and

$$FeS_2 - Fe^{++} - 2S^{=} + 2e^- = 0 \quad (19)$$

$$Eh = -1.38 - 0.0296 \log a_{Fe^{++}} - 0.0591 \log a_{S^-}. \quad (20)$$

At any assumed Eh and pH, a_{S^-} is fixed and $a_{Fe^{++}}$ in equilibrium with pyrite can be determined from equation 20. Similarly, $a_{Fe^{++}}$ in equilibrium with magnetite can be determined through equation (18). The magnetite-pyrite equilibrium boundary is then defined by a series of Eh-pH points at which $a_{Fe^{++}}$ is equal for the two relations.

Magnetite-Iron Sulfide Equilibrium.—As previously noted, a_{S^-} is fixed at any given Eh and pH. Thus at any assumed Eh and pH values $a_{Fe^{++}}$ in equilibrium with FeS can be calculated through the use of the activity product constant for FeS (18, p. 222);

$$a_{Fe^{++}} a_{S^-} = 10^{-15.4}. \quad (21)$$

Using equation (21) and equation (18) the magnetite-iron sulfide equilibrium boundary can be determined by exactly the same method used to determine the magnetite-pyrite boundary.

Hematite-Pyrite Equilibrium.—The equilibrium relationship between hematite and $a_{Fe^{++}}$ is given by

$$Fe_2O_3 - 2Fe^{++} - 3H_2O + 6H^+ + 2e^- = 0 \quad (22)$$

$$Eh = 0.727 - 0.177pH - 0.0591 \log a_{Fe^{++}}. \quad (23)$$

The hematite-pyrite equilibrium boundary can be determined through the use of equations (23) and (20) according to the procedure described in the section on magnetite-pyrite equilibrium.

Hematite-Iron Sulfide Equilibrium.—The hematite-iron sulfide equilibrium boundary can be determined through the use of equations (23) and (21) according to the procedure described in the section on magnetite-iron sulfide equilibrium.

Pyrite-Iron Sulfide Equilibrium.—The equilibrium relationship between pyrite and iron sulfide can be written as

$$FeS_2 - FeS - S^{=} + 2e^- = 0 \quad (24)$$

$$Eh = -0.84 - 0.0296 \log a_{S^-}. \quad (25)$$

If an Eh value is assumed, a_{S^-} in equilibrium with FeS and FeS_2 at that Eh can be determined. As a_{S^-} is fixed for any given Eh and pH, it only remains to find a pH value that will satisfy the above conditions. This can be

accomplished through the use of the relations given in the section on sulfide equilibria. Such a series of calculations will serve to define the pyrite-iron sulfide equilibrium boundary.

Siderite-Pyrite Equilibrium.—At any given Eh and pH values a_{S^-} is fixed and $a_{Fe^{++}}$ in equilibrium with pyrite and a_{S^-} can be calculated with equation (20). At any given pH value $CO_3^=$ is also fixed and $a_{Fe^{++}}$ in equilibrium with $CO_3^=$ and siderite can be calculated through the use of the activity product constant for siderite, equation (7). A series of Eh-pH points at which $a_{Fe^{++}}$ is equal for both relations will serve to define the siderite-pyrite equilibrium boundary.

Siderite-Iron Sulfide Equilibrium.—The siderite-iron sulfide equilibrium boundary can be calculated through the use of the activity product constants for siderite (equation (7)) and for iron sulfide (equation (21)). The method requires calculating a_{S^-} and $a_{CO_3^=}$ for a series of assumed Eh and pH values and the subsequent determination of $a_{Fe^{++}}$ values which will satisfy both relations simultaneously.

IRON MINERAL STABILITY DIAGRAM

The methods for calculating boundaries between stability fields for the various mineral pairs under consideration have been discussed in the preceding sections. Such a series of boundaries are shown in Figure 1 for a normal sea water system. To avoid crowding, the hematite-iron sulfide, magnetite-iron sulfide, and siderite-iron sulfide boundaries have been omitted. These boundaries, which would lie approximately 0.03 to 0.05 Eh unit below the respective hematite-pyrite, magnetite-pyrite, and siderite-pyrite boundaries, represent metastable equilibrium in view of the position of the pyrite-iron sulfide boundary and will not affect the final stability diagram.

Upon elimination of the mutually exclusive segments of the boundaries in Figure 1, a diagram showing the Eh-pH stability fields for hematite, magnetite, siderite, pyrite, and iron sulfide is obtained (Fig. 2).

An environmental position within one of the stability fields indicates that that mineral would tend to form in preference to the other minerals on the diagram, assuming of course, that the concentration of iron was sufficient. A position on any of the field boundaries would indicate that the adjacent minerals were in equilibrium with each other and could exist together. At the intersection of any three field boundaries, the three adjacent minerals would be in equilibrium with each other. Because of probable lack of complete thermodynamic equilibrium in most natural environments, it is likely that a zone of apparent stability of adjacent minerals would exist rather than a single boundary line along which they could occur together.

Pyrrhotite and other forms of iron sulfide approaching the composition FeS can form at low temperatures (1, p. 212; 26, p. 1329) and their presence in unmetamorphosed sedimentary rocks has long been reported in the literature (6, p. 234; 14, p. 117; 23, p. 750; 24, p. 6; 27). However, because of the compositional variability of pyrrhotite and the numerous uncertainties

regarding the mineralogical form of these other iron sulfides the FeS stability field on the diagram has not been assigned a mineral name.

The mineral smythite (Fe_3S_4) was recently described (9) but as yet details regarding its properties and occurrence have not been published. On the basis of its composition, however, its stability field would be expected to lie between that of FeS and pyrite.[2]

Thermodynamic data for iron silicates such as minnesotaite, chamosite, glauconite, greenalite, and others common to many iron-rich sediments, are

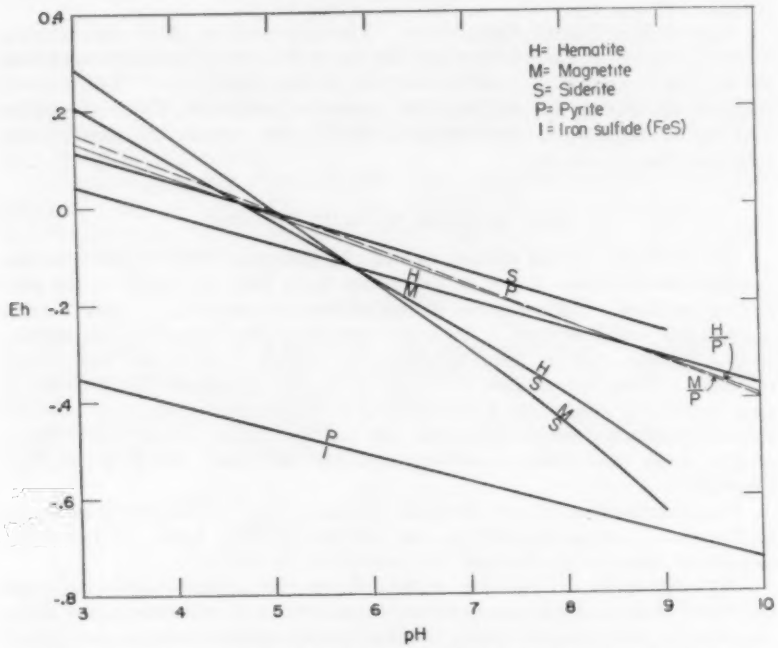

FIG. 1. Boundaries between Eh-pH stability fields for mineral pairs.

not available for use in plotting their stability fields. As ferrous iron generally predominates over ferric iron in these minerals, their stability fields would be expected to lie adjacent to or overlapping the present siderite and magnetite fields. This relationship is indicated by the intimate association of these silicate minerals with magnetite and siderite in many iron-formations.

[2] Since this manuscript was completed, smythite has been described in detail and the low temperature origin of both smythite and pyrrhotite in sedimentary rocks has been discussed (Erd, R. C., Evans, H. T., and Richter, D. H., 1957, Smythite, a new iron sulfide, and associated pyrrhotite from Indiana: Am. Mineralogist, v. 42, p. 309–333).

It is possible that maghemite (γ-Fe_2O_3) plays a role in the sedimentary iron mineral system although its presence as a primary or diagenetic mineral in sedimentary iron formations is uncertain. According to Mason (20, p. 116), maghemite can be formed either by the oxidation of magnetite or by the dehydration of leipdocrocite (γ-FeO·OH). He further notes that maghemite is metastable with respect to hematite and readily inverts to hematite under suitable temperature and pressure conditions.

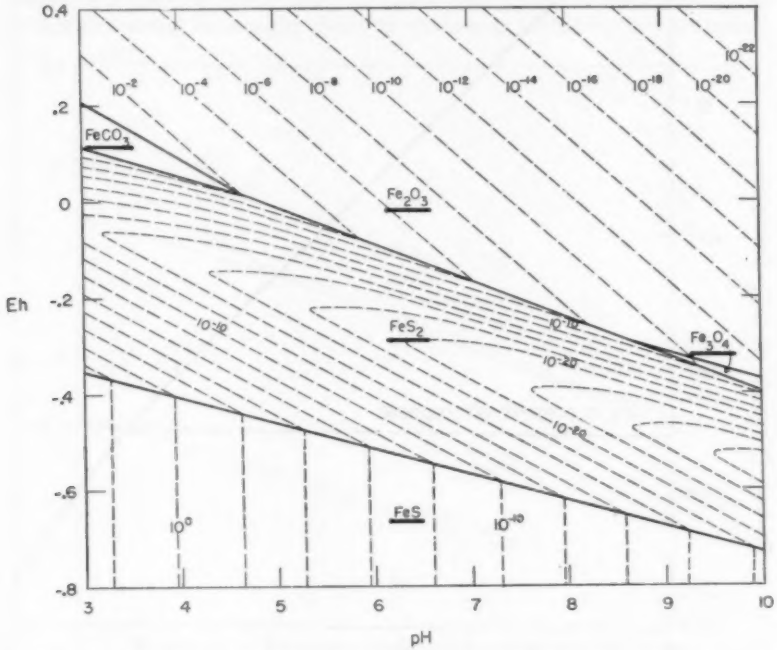

FIG. 2. Eh-pH stability fields for hematite, magnetite, siderite, pyrite, and iron sulfide (FeS) in normal sea water system. Contours indicate $a_{Fe^{++}}$ in equilibrium with the solid phases.

EFFECTS OF ADDITIONAL VARIABLES ON STABILITY FIELDS

Partial Pressure of CO_2.—The pH of most natural waters is chiefly determined by the concentration of carbonic acid and to a much lesser degree boric acid, as these are the only weak acids present in sufficient quantity to affect the hydrogen ion equilibria. Under anaerobic conditions the pH is also affected by H_2S. Figure 3, after Rubey (25, p. 1127) illustrates the relation between pH and the partial pressure of CO_2. The carbonate-ion concentration depends upon the dissociation of carbonic acid through the equilibria given in equation (8). Once the hydrogen ion concentration has

been established by the value of the CO_2 partial pressure, the carbonate-ion concentration follows directly. Thus a change in the partial pressure of CO_2 from that normally in equilibrium with the present atmosphere will shift the position of a natural environment in the Eh-pH diagram but will not appreciably change the shape or position of any of the mineral stability fields.

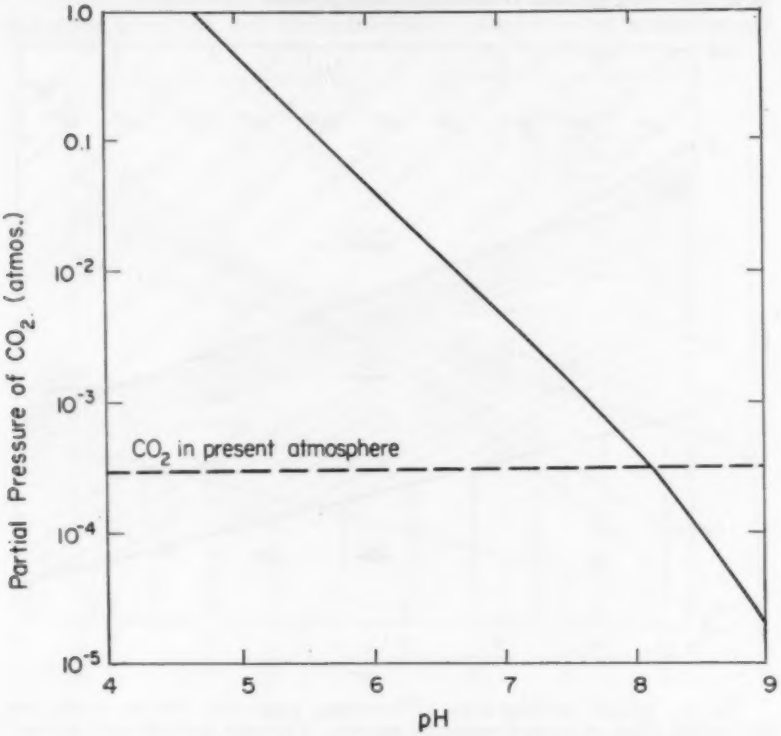

FIG. 3. Variation in pH of sea water as a function of partial pressure of CO_2 (after Rubey, 1951).

Several workers (cf. 19; 30) have suggested that the partial pressure of carbon dioxide in the atmosphere during the Precambrian was very much greater than that at the present time. On the other hand, Rubey (25) in his study of sea water-atmosphere relations concludes that radical changes in the atmosphere have not occurred during recorded geologic time, and James (16) in a discussion of the problem arrives at the same conclusion. The writer favors the latter view, but in either case, because of the direct relationship between pH and carbonate-ion concentration the environmental

considerations of this study will apply equally well to Precambrian as to more recent iron-rich sediments.

Sulfide Ion Concentration.—At any given Eh and pH the sulfide ion activity is fixed by the dissociation constants of H_2S and H_2SO_4 and by the potential equation (14) given in the section on sulfide equilibria, once a value for total sulfur in solution has been determined or assumed. Because changes in total sulfur content will produce changes in sulfide ion concentration, it is perhaps instructive to consider the changes in the stability diagram which would be brought about by changes in sulfide ion concentration.

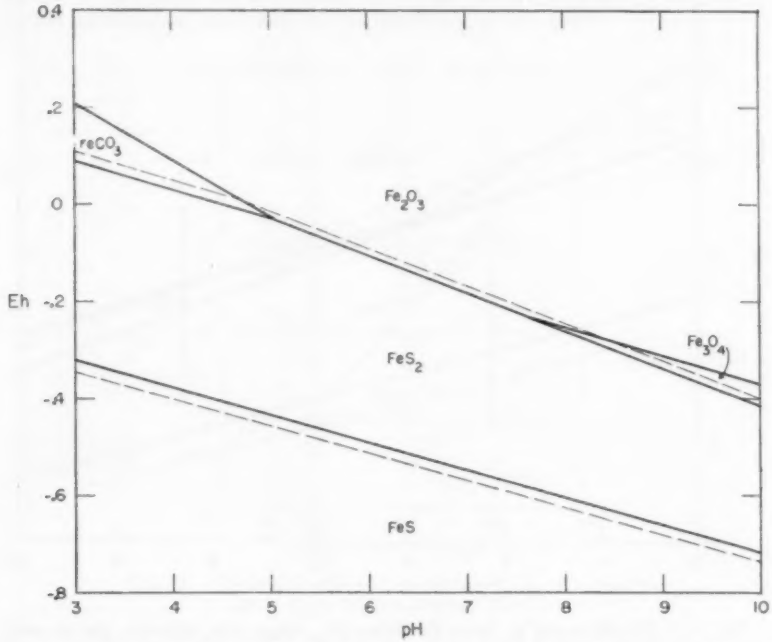

FIG. 4. Eh-pH stability fields for hematite, magnetite, siderite, pyrite, and iron sulfide (FeS) with carbonate equilibria as in normal sea water and total sulfur one-tenth that of normal sea water. Dashed lines for total sulfur as in normal sea water.

Figure 4 illustrates the change in the stability diagram which would be brought about by decreasing sulfide ion concentration to one-tenth that calculated for normal sea water. Figure 5 illustrates the change in the diagram brought about by further reducing the sulfide ion concentration to that encountered in average river or lake water. This is based upon the assumption of 17.7 ppm $SO_4^=$ and salinity of 146 ppm for average river and lake water (5) or approximately $10^{-2.2}$ times the concentration calculated for normal sea water.

Figures 4 and 5 show that the siderite-pyrite, hematite-pyrite, and magnetite-pyrite boundaries will be depressed to lower Eh values with decrease in sulfide ion concentration. The dashed lines in the diagram indicate the positions of the boundaries for normal sea water conditions and provide a measure of the amount of change. The lowering of the aforementioned boundaries produces a concomitant increase in the sizes of the siderite and magnetite fields. Increase in sulfide concentration above that in normal

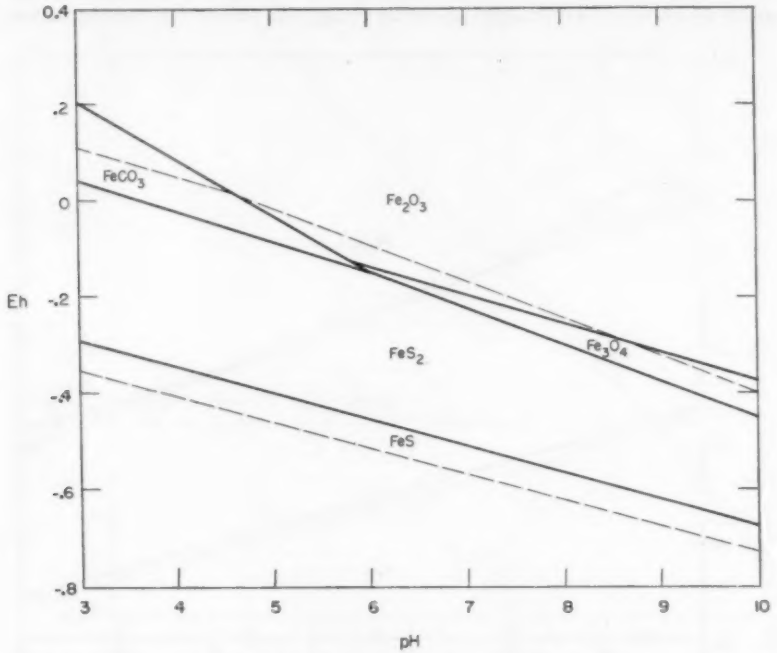

FIG. 5. Eh-pH stability fields for hematite, magnetite, siderite, pyrite, and iron sulfide (FeS) with carbonate equilibria as in normal sea water and total sulfur as in average river and lake water. Dashed lines for total sulfur as in normal sea water.

sea water would produce changes in the opposite direction but of the same magnitude.

Pressure.—The effect of pressure on the various equilibrium constants and relations used to calculate the stability field boundaries is in general not known. For a shallow depositional basin in which only moderate pressure increases will occur, the effect on hematite, magnetite, and pyrite is probably unimportant. The effect of pressure on siderite solubility is greater than that for the other minerals because of the carbon dioxide relations. Garrels and Dreyer (11, p. 340) note a very small increase in

the solubility of calcite within the pressure range to be expected in a moderately shallow basin and the effect of pressure on siderite solubility is probably similar.

Temperature.—The solubility of CO_2 in sea water as well as the dissociation constants of carbonic acid are affected by changes in temperature. However, the net effect of these changes is slight and only causes a pH drop of approximately 0.01 pH unit for a rise of 1° C over the intermediate pH range and in the temperature range from 0° C to 25° C (13, p. 54). The temperature range that is to be expected in normal marine environments probably does not generally exceed 10° C, so that the resulting variation of 0.1 pH unit can be neglected for the purposes of this paper.

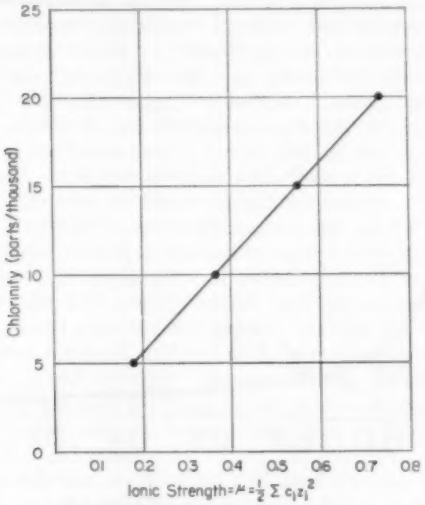

FIG. 6. Ionic strength versus chlorinity for sea water (after Garrels and Dreyer, 1952).

Temperature, as well as pressure, will cause changes in the $\Delta F°$ values of Table 1 used in the calculations. Within the temperature and pressure ranges under consideration these changes will be small.

Salinity.—The activity coefficient relates the activity of a given ion to its stoichiometric concentration through the formula

$$a_i = \gamma_i C_i,$$

where a_i is the activity of the ion, γ_i is the activity coefficient, and C_i is the stoichiometric concentration. The value of γ_i is chiefly dependent upon the valence of the ion and the ionic strength of the aqueous solution. The ionic strength is in turn dependent upon the salinity (or chlorinity) of the

sea water system. Figure 6 illustrates the relation between chlorinity and ionic strength and Figure 7 shows the relation between the activity coefficient of the carbonate ion and the ionic strength of the system. As activity coefficients were used only in the calculations that involve the carbonate and the sulfide ions, only those boundaries concerned with these ions will be affected by changes in ionic strength.

Changes in activity coefficients over the probable salinity range will be small. As salinity increases over that of normal sea water, the activity coefficients change very little, having reached nearly constant values under conditions of normal salinity (Fig. 7). As salinity decreases below that of normal sea water, the activity coefficients increase very slowly down to the

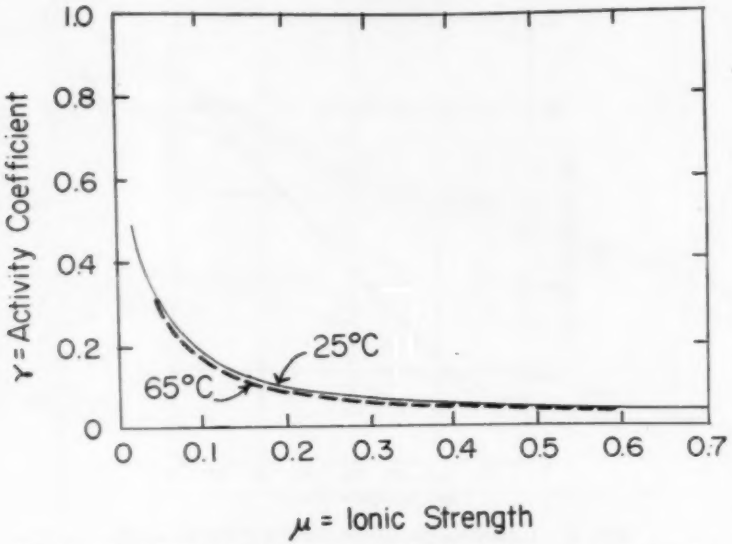

FIG. 7. Activity coefficient of the carbonate ion as a function of ionic strength (after Garrels and Dreyer, 1952). μ = approximately 0.7 for normal sea water.

range of very low ionic strengths. Thus, in any system that has an appreciable quantity of dissolved salts, the activity coefficients are relatively constant and the positions of the various mineral stability fields will not be changed by small variations in the salinity.

APPLICATION OF THE IRON MINERAL STABILITY DIAGRAM

Limitations of the Diagram.—Before considering the application of the Eh-pH diagram to environmental relationships it seems appropriate to review some of the assumptions used in the development of the diagram and to point out some of its limitations.

Some of the free energy values used in the calculations must be considered as only approximate. This is especially true for Fe_2O_3, Fe_3O_4, and FeS, for each of which several $\Delta F°$ values may be found in the recent literature. Any change in the free energy values used in the calculations will cause the field boundaries to shift, but remain parallel, thus causing an increase or decrease in the size of the various fields and a modification of the field intersections. The use of a smaller free energy for magnetite, for example, will shift the magnetite-hematite boundary toward higher Eh values, which would extend the magnetite stability field into part of that now occupied by hematite.

Another factor that might alter the size of the siderite stability field would be the probability of forming solid solution series with Mn, Mg, and Ca. The presence of these ions in the system would probably slightly increase the size of the siderite field.

The entire system of calculation assumes the presence of an aqueous medium of relatively constant composition and complete thermodynamic equilibrium between the solids and ions contained therein. Thermodynamics considers only the energy relations between reactants and the products of the reactions and makes no attempt to indicate the stages through which the reactants may have to pass or the rate at which equilibrium is attained. It is not possible with these data to assess quantitatively the effect of kinetics on the equilibrium systems. The relative rates of formation of the various minerals will exert some control over the primary deposition and this factor will be overcome only if sufficient time (and ionic mobility) is available for attainment of thermodynamic equilibrium.

Assuming that the free energy values used are approximately correct, the Eh-pH diagram as presented in Figure 2 indicates the stability relations between the various minerals under a given set of conditions: equilibrium with a normal sea water system. Because of the variability of some of these conditions, the value of the diagram lies in its indication of the relative positions of the various stability fields rather than in their exact numerical limits on the Eh and pH scales.

Magnetite Equilibrium Field.—As indicated by the Eh-pH diagram, hematite is stable under oxidizing conditions, siderite and magnetite under intermediate to mildly reducing conditions, and pyrite and iron sulfide under moderate to strongly reducing conditions. Magnetite, although stable under approximately the same Eh conditions as siderite, will form in preference to siderite under alkaline pH conditions.

The inclusion of a magnetite field in the iron-mineral stability diagram is in accord with numerous recent suggestions that magnetite is probably much more important as a primary or diagenetic mineral in sedimentary rocks than has generally been assumed.

Brown (3) discusses several occurrences of low-temperature magnetite and possible chemical reactions involved, and concludes that magnetite can be formed by "natural supergene or superficial low-temperature processes." James (16) reviews additional occurrences and the general problem of magnetite as a primary mineral in sedimentary iron-formations and reaches the same conclusion. White (32) in an examination of the mineralogy of the

Biwabik iron-formation of the Mesabi range concludes that much of the magnetite in that formation is of primary or diagenetic origin.

Most of the evidence upon which Brown, James, White, and others have reached their conclusions in regard to low-temperature magnetite has been based upon mineral associations and petrographic features in the rocks as observed in the field and under the microscope. The Eh-pH iron-mineral stability diagram supplements the field evidence by indicating within approximate limits the Eh-pH conditions under which magnetite can exist in a chemical sedimentary environment and its stability relationships relative to other important sedimentary iron minerals.

It has been demonstrated in the laboratory that magnetite can be precipitated from aqueous systems at low temperature and pressure. If alkali is added to a solution containing equivalent amounts of ferrous and ferric salts, a precipitate is obtained that is brownish-black, magnetic, and has an X-ray diffraction pattern identical with that for magnetite from other sources (31, p. 88; 28, p. 818). Hydrous Fe_3O_4 rather than hydrous Fe_2O_3 can be obtained by oxidation of ferrous hydroxide in an alkaline medium provided the rate of supply of oxygen is slow (31, p. 88); however, with a large supply of oxygen (high Eh) the rate of oxidation to ferric oxide is so high that little or no Fe_3O_4 is formed.

Causes and Effects of Lack of Equilibrium.—The failure of a chemical system to maintain equilibrium may permit a thermodynamically unstable mineral to form in preference to a stable one, with resultant anomalous mineral associations.

If magnetite were to be excluded from the Eh-pH mineral stability diagram, the hematite field would be extended into much of what is now the magnetite field. Thus if magnetite were to be retarded from forming because of differences in the relative rates of formation of magnetite and hematite, hematite might first precipitate as a thermodynamically unstable phase under conditions where magnetite is the stable phase. Presumably, as the system approached equilibrium, magnetite would form at the expense of hematite. Lack of complete equilibrium might allow considerable hematite to remain although it would be thermodynamically unstable. This would permit the original precipitation of hematite under conditions of magnetite equilibrium and would also expand greatly the apparent range of conditions under which hematite and magnetite might occur together.

Lack of equilibrium may also result from the failure of a system to respond to environmental changes. If, for example, hematite should form under conditions of hematite stability, and the environmental conditions then be changed to those appropriate for the formation of magnetite, magnetite should tend to completely replace the hematite. The failure of this reaction to proceed to completion because of insufficient time or restriction of ionic mobility would result in lack of equilibrium and the formation of a mixture of hematite and magnetite rather than magnetite alone.

The sulfide-sulfate relationship provides an example in which a biologic catalyst may play an important part in the kinetics of the system. As noted by Pettijohn (21, p. 458) and by Galliher (10) the source of sulfide for

the formation of pyrite is twofold; bacterial reduction of sulfates in sea water, and of less importance, sulfur derived by bacterial action on sulfur tied up in previously existing organic compounds. The presence of bacteria for the reduction of sulfate is necessitated by the apparent inability of a natural inorganic system to reduce sulfate to sulfide at ordinary temperatures (2; 12; 33; 8). Therefore, in the absence of sulfide of organic origin or of sulfate-reducing bacteria, iron sulfide (or pyrite) may fail to form even though it is thermodynamically stable and the Eh is low enough to permit reduction of available sulfate. This would produce a metastable extension of the siderite and magnetite fields to lower Eh values.

Seemingly anomalous mineral associations may be produced as a result of extremely local environments, such as in a zone of low Eh surrounding a fragment of organic material in an otherwise oxidizing environment. Under such conditions pyrite might be formed locally in a sediment in which hematite is the stable mineral elsewhere.

In spite of the difficulties involved in its application, the Eh-pH iron-mineral diagram does indicate equilibrium relationships under the specified conditions—relationships that are relatively insensitive to minor changes in these conditions. In addition to predicting the mineral associations to be expected under equilibrium conditions it will to some extent indicate the degree of lack of equilibrium in natural mineral occurrences.

U. S. GEOLOGICAL SURVEY,
MENLO PARK, CALIF.,
July 8, 1957

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FACTORS CONTROLLING THE LOCALIZATION OF ORE DEPOSITS IN THE SHULLSBURG AREA, WISCONSIN–ILLINOIS ZINC–LEAD DISTRICT

ROBERT R. REYNOLDS

ABSTRACT

The majority of the zinc-lead orebodies near Shullsburg, Wisconsin are of the pitch-flat type first described by T. C. Chamberlin. A study of about 1,000 exploratory churn drill holes shows conclusively that solution of two limestone members (Oilrock and Glassrock) in an otherwise dolomitic section has been largely responsible for the formation of the pitch-flat structure in which the ore occurs. It has been possible to correlate the degree of solutional thinning of the Oilrock and Glassrock with the thickness of ore mineralization. Thus, the greater the thinning by solution, the more extensive the collapse of the overlying competent beds, forming the pitch structure. Correspondingly, incipient to poorly developed ore deposits show much lesser degrees of solutional thinning of the limy members.

Successful exploration techniques are discussed with emphasis on structure, degree of solutional thinning, and halo mineralization as the chief criteria to be used in finding an ore deposit.

It is hypothecated that minor adjustments of the Precambrian basement rocks have been responsible for the complex minor folding in the overlying Paleozoic sediments. It is further hypothecated that a large body of magma was intruded into the Precambrian rocks underlying the district, but did not rise high enough to send out any apophyses into the overlying sediments. This hypothetical body of magma is also suggested as the probable source of the mineralizing agencies which were able to rise into the overlying sediments through faults in the roof of the pluton.

INTRODUCTION

THERE have been many geological studies made of the Wisconsin-Illinois Zinc-Lead District. Most of these studies have treated the general geology so extensively as to obviate lengthy repetition here. Therefore, it is the intention of the writer to concentrate as much as possible on the origin of the ore deposits and the problems connected with exploration for these deposits.

GENERAL GEOLOGY

The Upper Mississippi Zinc-Lead district lies almost wholly within the unglaciated or driftless area in Southwestern Wisconsin, Northwestern Illinois and a narrow belt along the Mississippi River in Northeastern Iowa.

The topography is mature and a maximum relief of about 800 feet exists between the level of the Mississippi River and the top of Platte Mound, 2 miles east of Platteville.

A relatively thin veneer (1,500–2,000 feet) of sediments of upper Cambrian, Ordovician and lower Silurian age covers the crystallines of the basement

complex. The lower Silurian sediments cover but a very small portion of the district as its southern boundary roughly coincides with the Silurian escarpment.

The district lies on the west flank of the Wisconsin Arch and the regional dip of the strata is to the southwest at about 15 feet to the mile. The sediments have been gently folded. The fold axes have three prominent trends; east, northeast, and northwest. The folding was accompanied by jointing, generally parallel to the above fold trends, with some north-south jointing. Some faulting is present in the district, but it is of a minor nature. The

FIG. 1. General location map of the Upper Mississippi Zinc-Lead District.

largest folds in the area strike approximately east-west. These are the Savanna-Sabula anticline, Meekers Grove Arch and Mineral Point anticline. Between these large anticlines are the second and third order folds forming a network pattern of northeast and northwest trends which are crossed by a few minor east-west folds (Fig. 4).

The important zinc deposits are closely associated with the synclinal portions of the minor folds. The ore deposits are generally elongated in the direction of the axial trend of the synclines in which they occur where the trend is either east-west or northwest. In the case of the northeast trending synclines the orebodies generally take the form of a horseshoe and are located

at intersections with east-west synclines. The horseshoe type orebody may be completely developed so that it forms an ellipse around a small synclinal basin. However, the most common occurrence of the horseshoe type deposit is around the end of a plunging syncline. Rarely they may form around the nose of a plunging anticline. In the area between Hazel Green and Shullsburg where the horseshoe type predominates, at least 90 percent of these deposits are turned so that the closed end of the horseshoe is to the east.

BRIEF SUMMARY OF THE IDEAS ON THE ORIGIN OF THE ORE DEPOSITS

The source of the mineralizing solutions has long been a subject of controversy among geologists who have studied the area. Until about 1925 the district was considered to be an outstanding example of "cold water" deposition. It was believed that descending meteoric water leached the metals from the country rock where they were present in minute quantities as original constituents. The metals were then thought to have been carried downward and precipitated from the ground water by the agency of hydrogen sulfide derived from certain members high in organic matter. Since 1924, when Spurr (12) suggested an ultimate magmatic origin for the mineralizing solutions, more and more emphasis has been directed towards this point of view. The great amount of data accumulated in the last 25 years have confirmed the hydrothermal theory for the origin of these ore deposits.

The mode of formation of the main lower-run ore-bearing structures, or receptacles, has been the subject of lengthy discussion in most of the studies on the district. There have been almost as many ideas on the formation of the receptacle as there have been students of the problem. Briefly these ideas may be classified into two categories: 1) collapse and 2) tectonic. The early studies of Chamberlin (5), Jenney (10), and Grant (7) emphasized the role of tectonics in the formation of the lower run pitch-flat receptacle which is the dominant ore-bearing structure in the district. Bain (2) and Cox (6) believed that the pitch-flat ore receptacles were formed by collapse; the former attributed this to differential compaction of the Oilrock while the latter suggested that solution of the Oilrock was the cause of the collapse. Spurr (12), Scott (11), Behre (3, 4), Heyl and Agnew (9) have emphasized the tectonic control on the localization of orebodies and in the formation of the pitch-flat structures. Recent work by Willman (13), and Willman and Reynolds (14) has re-emphasized the role of solution and collapse in the formation of the pitch-flat receptacle. The present study attempts to evaluate the relative importance of tectonics and solution and collapse in the formation of the lower run deposits. Considerable quantitative data are presented from a statistical analysis of drilling results that confirm the basic concepts of the solution-collapse theory.

SOURCES OF THE DATA USED IN THIS STUDY

The writer was fortunate to have been present during most of Calumet and Hecla's intensive exploration campaign. To date over 1,000 exploratory holes have been drilled, and they have led to the development of substantial ore reserves. Much of this drilling has been distributed over a great many

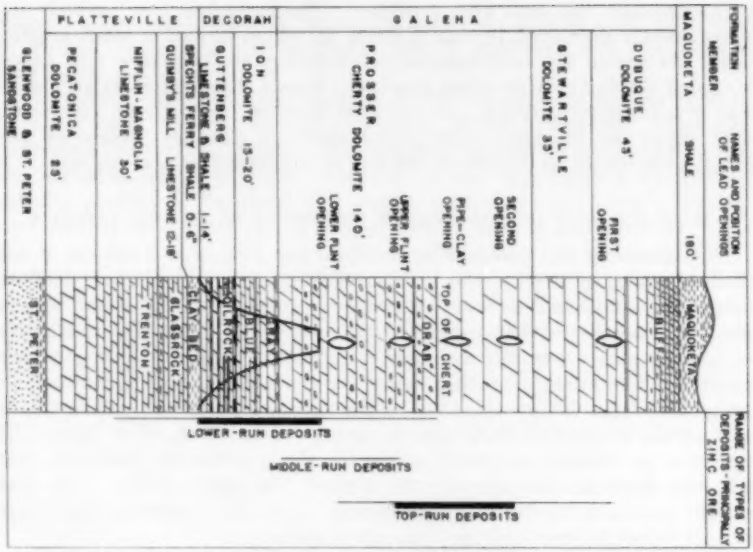

FIG. 2. Stratigraphic range of ore deposits in the eastern end of the Hazel Green-Shullsburg area. (Adapted from drawing in Rept. of Investigations 116, Ill. State Geol. Survey.)

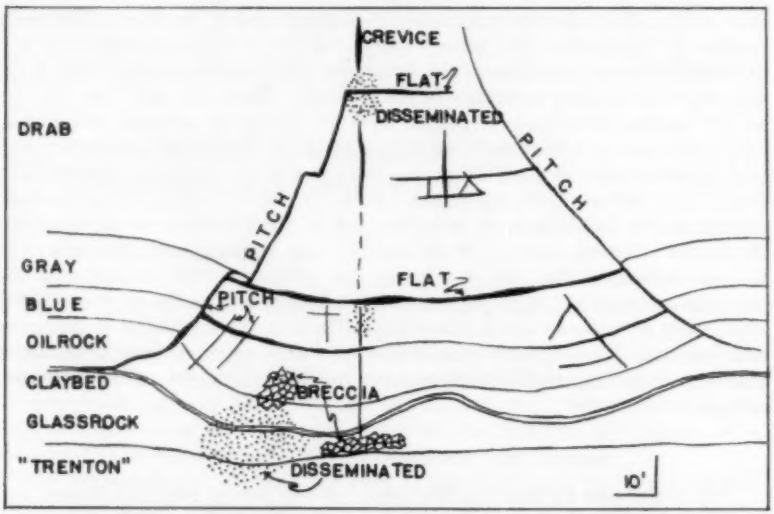

FIG. 3. Diagrammatic cross-section showing types of occurrence of ore in lower-run deposits. (Adapted from drawing in Report of Invest. No. 116, Ill. State Geol. Survey.)

square miles so that a perspective was gained of the larger relationships of the deposits to the regional structure, as well as the detail in and adjacent to the orebodies.

Most of the data used in this report have come from the eastern end of the intensively mineralized Hazel Green-Shullsburg area. It may be argued that these data do not adequately represent the conditions in some other parts of the district. It is true that there are minor differences in the stratigraphy of the ore zone such as the very thin to virtually absent claybed and the thicker than average Glassrock (refer to Fig. 2 for stratigraphic relations and terminology). Also there appears to be more Glassrock and Trenton ore in the Shullsburg area than is characteristic of most of the district. However, deposits of nearly every type recognized in the district have been found in the Shullsburg area. These include "top run" lead and zinc, "middle run" zinc in both openings and "brangle," and nearly all types of "lower run" deposits, such as linear pitch-flat orebodies, horseshoe pitch-flat orebodies, disseminated Oilrock runs, Glassrock runs, and Trenton ore. Most of the above types of ore occurrence are commonly associated in the larger orebodies (Fig. 3).

The Shullsburg area represents a definite extention of the district. This area is unique in that a large proportion of the discoveries have been under the Maquoketa shale; in some cases as much as two miles from the nearest outcrop of the Galena formation. Probably the main reason that the area south of Shullsburg did not receive attention during the pre-World War I activity was the acceptance, at that time, of the descending (cold water) theory for the deposition of the ore of this district. The Maquoketa shale, according to this theory, was supposed to inhibit the downward circulation of meteoric waters thus preventing the formation of ore deposits under the areas it capped. Another reason the area was not prospected was due to the much deeper drilling involved and the resultant higher costs for exploration.

STRATIGRAPHY

The following table represents the normal thickness of the various beds in the section where there has been no solutional thinning.

Max. thickness	Formation	Max. thickness	Member	Mining terminology
185′	Maquoketa Sh.			Maquoketa
		45′	Dubuque	Buff (down to top of cherty Prosser) Drab (lower 100′ of cherty Prosser)
220′	Galena Dol.	35′	Stewartville	
		140′	Prosser	
				Gray
32′	Decorah Ls. & Dol.	20′	Ion	Blue
		12′	Guttenberg	Oilrock
		0–6″	Specht's Ferry	Claybed
75′	Platteville Ls. & Dol.	18′	Quimby's Mill	Glassrock
		30′	Magnolia-Mifflin	
		25′	Pecatonica	Trenton

Relation of Mineralization to the Stratigraphy

Maquoketa Shale.—185 feet thick. This formation is a blue-gray, somewhat calcareous shale with a few thin argillaceous limestone beds. The only mineralization noted is at the base of the formation, which is, at most, only a few inches thick and contains abundant, pyritized, dwarfed fossils. A few drill holes also show a little sphalerite and galena at this zone.

Buff and Drab Members (Galena formation).—220 feet thick. This formation is commonly subdivided by mining terminology into only two members, the Buff and the Drab. The Buff consists of 45 feet of thin to medium-bedded, somewhat argillaceous dolomite and 75 feet of very pure massive-bedded dolomite. The Drab consists of 100 feet of cherty dolomite, the chert occurring as nodules or thin beds. The lower 10 feet is generally chert free, as are several other 5 to 10 foot intervals within the member.

The highest of the commercial lead deposits occur about 40–50 feet below the top of the Galena formation and may extend downward nearly to the top of the Gray (Fig. 2). The "top run" deposits are confined to "openings" that were probably formed by solution action along the more open joints at favorable horizons. The higher "openings" rarely contain much sphalerite, but in places the lower ones may be much more heavily mineralized by sphalerite than by galena.

The lowest deposits of "top run" type may be more or less transitional to those described as "middle run" which generally occur in the lower half of the drab member. The "middle run" deposits are generally in narrow openings, the walls of which are encrusted with sphalerite and minor amounts of galena. The richest deposits worked during the early days of zinc mining were of this type. Another variation of the "middle run" deposits are those of "brangle" type. The "brangle" deposits may be very much larger than the long, narrow, joint opening deposits. "Brangle" ore consists of the vugs in the country rock that are more or less completely filled by sphalerite, marcasite and a little galena. Very often the first clue to ore deposition in an area being prospected by drilling will be the repeated encountering of "brangle" mineralization in the lower part of the Drab member. It is considered to be a very favorable indication of the presence of "bottom run" deposits in the vicinity. However, if any of the requisite factors for the formation of the "bottom run" receptacle are not present there will be little or no lower ore associated with the "brangle" deposit.

Gray Member (Decorah formation).—10–15 feet thick. This member is a light-to-medium-gray dolomite, medium-grained, and containing some green shale partings. The Gray may be the highest member containing "bottom run" pitch and flat mineralization, though generally strongly developed pitches continue upward for 20 feet or more into the lower Drab. However, it is quite common for the pitch to terminate in a prominent flat at the top of the Gray. Vugginess is common in the Gray in an orebody and the vugs are commonly more or less filled with the ore minerals.

Blue Member (Decorah formation).—6–10 feet thick. The Blue is a medium-to-dark-gray dolomite, medium-grained, with numerous green shale

partings. It commonly alters in an orebody to a mixture of dolomite grains in a light-blue clay residue. It is generally not well mineralized, although in the altered phase it may contain some disseminated sphalerite and in many places may be almost completely replaced by marcasite.

Oilrock Member (Decorah formation).—1–14 feet thick. In its thickest phase the Oilrock is a thin-bedded light-buff to pink fossiliferous limestone with brown carbonaceous shale partings. In the thinned phase a considerable portion of the limestone has been removed by solution leaving a residue of the shaly partings. Generally the remaining limestone beds have been more or less dolomitized.

The pitches generally originate in the Oilrock near its base and step upward at approximately 45° through the overlying beds until they reach the top flat. In certain instances, believed to be rare, the pitch may originate in the Glassrock (below the Oilrock) and continue unbroken upwards to the top of the orebody.

It is not uncommon to find disseminated ore in the Oilrock where the rock is in a softened or residue[1] phase. Oilrock ore may occur either as a part of pitch-flat deposits or in disseminated deposits where a pitch did not develop.

Claybed Member (Specht's Ferry member of the Platteville formation).—This is present generally as a thin shaly parting but may be a thin gray-blue shaly limestone up to a few inches in thickness.

This member contains no ore of commercial significance and, where mineralized, it is only by scattered euhedral crystals of sphalerite.

Glassrock Member (Quimby's Mill member of the Platteville formation).—10–18 feet thick. This member is a very fine-grained buff to brown limestone, generally in beds a few inches thick, with a few thin partings of dark-brown shale. There are a few inches of dark-brown shale at or near the base.

The Glassrock may be thinned considerably by solution and, where this occurs, it does not tend to soften or develop residue as prominently as does the Oilrock. The brittle nature of the rock causes it to be considerably brecciated in areas of disturbance, and where mineralized, the ore fills and partially replaces the breccia. Miniature pitches generally die out near the top of this member, though rarely (as described above) they continue unbroken into the higher formations.

Glassrock ore is found in all of the deeper orebodies. In those of pitch-flat type the Glassrock ore does not underlie the whole orebody but appears to roughly parallel and remain under the "toe" of the main pitch. Glassrock ore seldom attains a width over 75 feet.

Many Glassrock runs have been found that seem to have no connection with pitch orebodies. Others may alternate along the strike of the deposit from Glassrock ore only, to both Glassrock and pitch ore, and then back to Glassrock ore. This cycle may be repeated several times in one deposit.

[1] In and adjacent to "lower run" deposits, the Oilrock has been a subject to more or less solution with removal of lime leaving an argillaceous and carbonaceous residue as explained in a later section.

Upper Trenton Member (Magnolia-Mifflin member of the Platteville formation).—15–30 feet thick. This is the lowest of the three predominantly limestone members in an otherwise dolomitic section. The rock is light mottled blue-gray in color, dense, and somewhat argillaceous. The upper portion (Magnolia) is more dolomitic and less subject to solution and softening than the lower portion (Mifflin). Where ore occurs in this member the

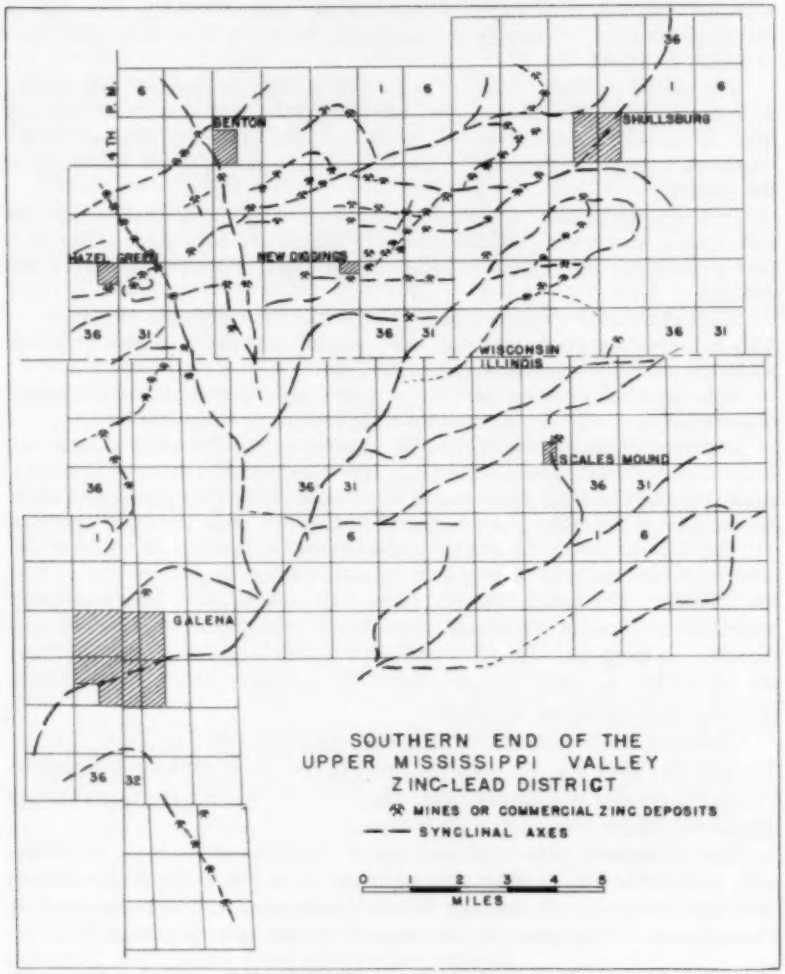

FIG. 4. Synclinal Axes map. (Adapted from maps of the Ill. Geol. Survey, U. S. Geol. Survey, and Calumet and Hecla, Inc.)

rock has always been somewhat thinned and softened by solution. Generally mineralization in the upper Trenton takes place by replacement, but "sheet ore" is common where the member is well mineralized. Quantitatively, Trenton ore is less important than any other portion of the "bottom run" deposits.

Lower Trenton Member (Pecatonica member of the Platteville formation). —This member is about 25 feet thick. It is a light buff to gray dolomite, fairly dense and somewhat argillaceous. It is not known to contain commercial amounts of sphalerite or galena. It does not show any evidence of solutional thinning and any mineralization observed in it has been in minute fracture fillings or an occasional crystal in the infrequent vugs.

STRUCTURE OF THE SHULLSBURG AREA

From New Diggins, Wisconsin eastward (Fig. 4 and U. S. Geol. Survey map), the area has been folded into a series of northeast trending anticlines and synclines, the closure of which seldom exceeds 20–30 feet. The synclinal axes, measured at right angles to their strike, are approximately 1 mile apart. The anticlines tend to be somewhat wider than the synclines. As the orebodies generally show a close relationship to the synclines, drilling widely spaced holes to determine structure eliminates over 50 percent of the area under consideration.

The axis of a large anticline, the Meeker's Grove arch, is located about two miles north of the city of Shullsburg. The strike of this fold is about S 80° E at this point. The dip on the south limb averages about 50 feet per mile while the north limb dips up to 100 feet in ¼ of a mile near Meeker's Grove. For comparison, the average regional dip is about 20 feet per mile in a south-southwesterly direction. The presence of this strong anticline has apparently exerted a profound influence on the behavior of the northeast trending synclines as they approached the arch.

The city of Shullsburg is located at about the point where the formations begin to rise northward towards the crest of the arch. About 2 miles due west of Shullsburg, the northeast trending syncline that contained many large orebodies from New Diggings northeastward, culminated in the James-Doyle-Harty orebody, one of the largest in the district. The syncline and the orebody turn from a north-east trend, to north for about ½ mile and then to the west for about another ½ mile. This "wrapping around" or convolution is particularly characteristic of the structure immediately south of Shullsberg.

Only one northeast trending syncline is known to have continued across the Meeker's Grove arch in the vicinity of Shullsburg. This syncline was tested north of the city and found to be barren. The outstanding characteristic of this syncline is its closure of 40–50 feet, about twice that of the synclines associated with orebodies south of the city.

The pronounced convolute structure is the dominant feature of the synclines south of Shullsburg. They repeat the pattern shown by the James-Doyle-Harty syncline 2 miles west of Shullsburg. The inner closed synclinal loop contains the Kitto, N. Hayden and S. Hayden orebodies. The next

outward loop structure is associated with the Hancock, Winskell, Jamieson-Rooney, and Gensler orebodies. At the point where this structure turns northward, one mile east of the S. Hayden orebody, there is a small marginal deposit, the White-Rennick-McCoy. A mile north of this small orebody the syncline swings westward to join the inner loop syncline about at the Kitto orebody. The outermost loop structure on which there are sufficient data to map is associated with the Blackstone and possibly the Gensler-Edgerton orebody. This outermost loop turns northward about 2 miles east of the S. Hayden, curves westward and passes just south of the Shullsburg city limits, where it is joined by the sharp northeast trending syncline, previously discussed, that crosses the Meeker's Grove arch. Just west of this junction, and located in the main syncline, east-west at this point, is the Copeland mine. West of the Copeland mine the structure turns southwesterly and associated with it are the Lyne and Andrews mines.

ORIGIN OF THE FOLDING AND ATTENDANT FRACTURING

It does not appear, to the writer, that any satisfactory explanation of the structural complexities of the district is contained in the literature. Many students of the district have suggested that horizontal acting tectonic forces, transmitted by the sediments, were the cause of the folding. These tectonic forces have been variously supposed to have acted in northerly, northeasterly and northwesterly directions. Some geologists have thought that the tectonic forces acted in more than one of the above directions and possibly at different times. Heyl (8) has suggested that northeast directed forces may have originated from the Forest City basin to the southwest in Iowa, and north directed forces may have originated from the Illinois basin to the south. Heyl also describes the area as being an example of incipient Appalachian type folding.

There are a number of conditions in the district that are not adequately explained by horizontal acting forces, even if several directions in which these forces acted are hypothecated.

First, there is only a very thin veneer of sediments (approximately 1,500 feet) above the basement complex. It seems unlikely that there was ever more than 2,500 to 3,000 feet of sediments in the area before erosion stripped off some of the cover. This thin veneer of relatively weak sediments above the basement complex seems incompetent to transmit over long distances forces of the magnitude required to produce the folding observed in the district.

Second, the widespread existence of east-west tension fractures is another condition difficult to explain by simple horizontal acting tectonic forces. East-west is by far the most important fracture direction in the formation of both lead and zinc deposits. These fractures are relatively open and allowed easier ingress for the mineralizing solutions. In the Hazel Green-Shullsburg area, east-west fracturing has a definite northeasterly trending *en echelon* arrangement. This is shown in a broad way by the aerial distribution of the heavy zone of lead "diggings" that begin about 3 miles north of Galena, Illinois, and extend northeasterly almost to Shullsburg. The northeasterly *en*

echelon arrangement of the zinc deposits is most strikingly shown between New Diggings and Shullsburg (1). The zinc deposits south of Shullsburg show the same *en echelon* pattern but the bearing of the pattern is more northerly than the New Diggings-Shullsburg group.

Third, the northwest trending synclines present a special problem in themselves. Here the fracture pattern parallels the folding, the ore following the more heavily fractured zone more or less centrally located in the syncline. These northwest synclines are not as intensely folded as are the northeasts or east-wests. In fact, the deepest synclines in the area (Fig. 4) are northeasterly; the longest and deepest (maximum of 60 feet closure) is the one traced from the Mississippi River 2 miles southwest of Galena almost to Shullsburg. As pointed out above, the orebodies following the northeast trends have a predominant east-west strike and almost never do they parallel the trend of the syncline, a marked contrast to the northwest trending orebodies. Another peculiarity of the northwest synclines is their continuity over several miles without being accompanied, on either side, by equally continuous anticlines. In other words, they are more like troughs than folds. Orebodies associated with the northwest troughs appear to be much more highly fractured by vertical joints or shears that parallel the strike of the orebody, than other types of deposits. These joints or shears have opened up as much as several feet in places indicating tension may have played an important part in their formation. Considerable brecciation is apparent along some of the fractures and as no marked vertical displacement has been noted in the bedding, any shearing movement that may have occurred must be assumed to have been in a horizontal direction. It may be that minor shearing movements on the vertical fractures have caused the opening due to irregularities of the fracture walls rather than tension. Intersections with crossing structures, either east-wests or northeasts, seem just as important as loci for orebodies in the northwest troughs as it is for the other types of deposits. Apparently the additional shattering in these areas of intersection not only provided the necessary plumbing with the deep seated source of the ore-bearing solutions but also the required permeability at the horizon at which the ore receptacles were formed.

Suggested Revision of Ideas Concerning the Structure of the District

After having found fault with the generally accepted ideas of the mechanism responsible for the folding and fracturing of the district, the writer feels obligated to offer some suggestions of his own on rather tenuous evidence, it must be admitted.

It is suggested that minor faulting and readjustment in the basement rocks within the Wisconsin-Illinois district may have been responsible for the minor folding in the overlying sediments. For instance, the Meekers Grove arch is essentially a monocline that may well be the surface expression of a normal fault in the basement rocks, the north side being down thrown. A reasonable amount of normal faulting in the basement rocks would produce sufficient crustal elongation in the area to account for all the folding in the sediments.

Some faulting in the basement rocks is also indicated by the less direct evidence of the mineralization itself. By what more plausible method could the mineralizing agencies have gained access to the sediments in which the ore was deposited? All the evidence points to a deeply buried magmatic source for these mineralizing agencies. It seems most probable that the upward pressure and stoping action of this magma may well have caused dislocations in the basement rocks though it is probable that this magma did not rise high enough to contact the Paleozoic sediments or surely some dikes or apophyses of the magma would have been recognized in the district.

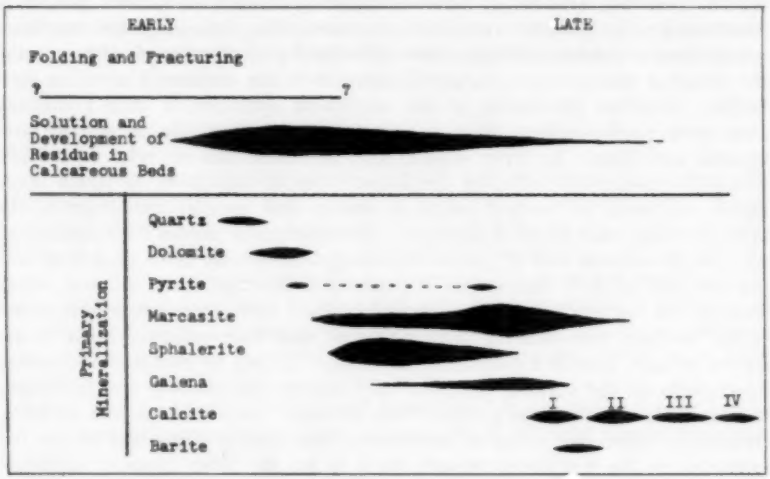

FIG. 5.

PARAGENESIS

Figure 5 is a simplified picture of the sequence of events leading up to and including the formation of the ore deposits of the Shullsburg Area.

Heyl (8, p. 198) has described the four calcite stages very thoroughly. The above diagram follows his paragenesis with the omission of some minor minerals (chalcopyrite, millerite and cobaltite). There is a marked disagreement with Heyl's diagram with the times at which solution began and ended. In addition, barite has been placed after calcite I because numerous occurrences have been noted of mamillary masses of barite coating and often partially replacing calcite.

ZONING

It appears that timing, in respect to the paragenesis of the ores, played a very important part in determining whether the receptacle was mineralized by all of the sulfides or received nothing but the very last minerals to deposit.

Every orebody is an individual in this respect and the incipient deposits commonly show a variety of conditions along their strike.

First it is necessary to consider the time interval through which solution occurred. Most of the limestone members may show some silicification of their residue phases so that it is obvious that some solution began with the earliest stage of mineralization. However, it is believed that solution of the calcareous members was not as widespread before the silica stage as later. In some mines, such as the Liberty and Hoskins, discussed by Heyl (8, p. 190), the mineralizing solutions were so heavily charged with silica that the calcareous rocks were partially to completely replaced, particularly near the conduit fractures.

Having established a probable limit for the beginning of solution, it is equally important to determine when solution ended. Heyl (8, p. 196) believes that solution of the limestone wallrock ended abruptly at the end of sulfide deposition. He says, "Apparently when the solutions were able to dissolve limestones, they were also able to precipitate sulfides, probably in part owing to the changes in composition of the solutions resulting from the

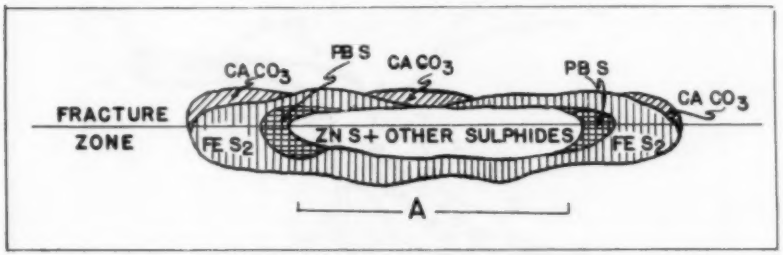

FIG. 6. Plan view of zoning relations in a typical ore deposit.

dissolving of the limestones." The preference of most sulfides for limestone country rock is well recognized, but this argument is in direct opposition to Heyl's (8, p. 18) giving the Liberty and Hoskins mines as examples of heavy silicification and resultant very low solution, yet both deposits were richly mineralized by sulfides. Heyl's (8, p. 197) description of the four calcite stages lists etched surfaces as one characteristic of the two earliest stages. As deposition of all sulfides, except a very minor amount of marcasite, had ceased by the end of calcite II stage, it is obvious that solutions possessing at least moderate dissolving power existed at least to the end of calcite II deposition. Sphalerite and galena are generally strongly etched where they occur in the larger openings such as the pitch and top flat. Also it has been noted that calcite of stages I and II fill brecciated Glassrock and solution softened Trenton within a few feet of heavy sphalerite deposits. Had these openings been present during the sulfide deposition they would most certainly have been mineralized by sulfides. Therefore, it seems most likely that some solution of the limestone country rock continued very nearly to the end of the hydrothermal mineralization.

All of the Shullsburg orebodies have fringes of minerals belonging to the later stages of the ore deposition. This fringe is generally much more extensive on the ends of the orebody than along the sides and commonly consists of heavy marcasite, calcite, and minor amounts of galena. It is not uncommon to find galena relatively concentrated near the ends of the orebody. Concentrations of the late minerals are also found above and below the deposits.

The zoning relations indicate that the ore-bearing solutions entered originally along a limited length (A) of the fracture zone. Solution of the limestone members is generally most intense in the zone where sphalerite is the important sulfide. As mineralization progressed, solution action continued to lengthen the receptacle by dissolving the limestone country rock bordering

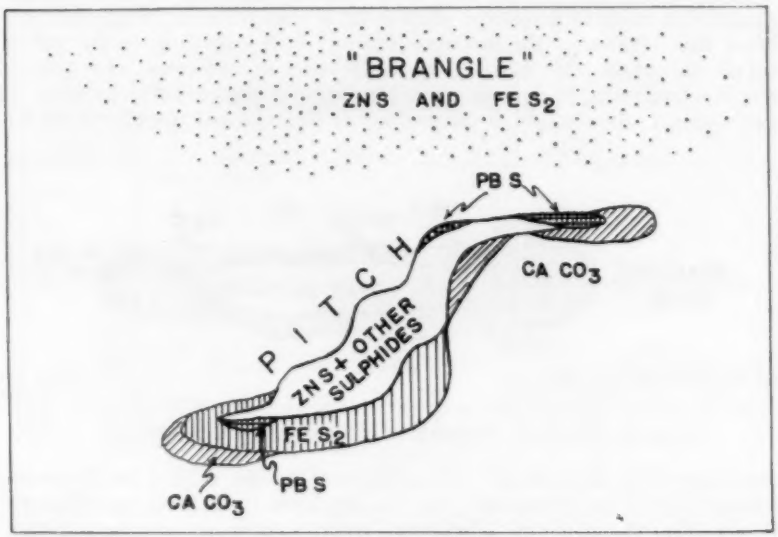

FIG. 7. Cross-sectional view of zoning relations in a typical ore deposit.

the fractures. After the end of sphalerite deposition it is obvious that any later openings would contain only minerals later in the paragenetic sequence.

It may be pointed out that any sphalerite found in the marcasite zone discredits this hypothesis. It would, to a degree, if the sphalerite were in open fissure type veins that, according to the hypothesis, could not exist without solution and collapse having formed the necessary openings before or while sphalerite was depositing. However, all of the sphalerite noted in the fringe zones appears to be of the "brangle" or vug filling type and is almost always restricted to the lower Drab, Gray and Blue members. This vugginess developed early and this type of zinc mineralization may be very widespread, particularly in the lower Drab. Thus, the occurrence of a small amount of sphalerite within the outer zones of the deposit is accidental.

THE ORIGIN AND DEVELOPMENT OF THE ORE RECEPTACLE

The origin of the arcuate orebodies will not be discussed because of the lack of information on this type of deposit. The arcuate type undoubtedly occurs in areas of greater structural complexity but that need not imply that the fundamentals governing their formation should necessarily differ from those governing the formation of the east-west linear type.

It is believed that the fracturing that has determined the location of the orebodies is tectonic in origin, but that the pitches themselves are seldom, if ever, reverse faults as advocated by Heyl and others. The pitch-flat ore receptacle owes its existence to the utilization of the tectonic fractures by the mineralizing agencies that dissolved up to 50 percent of the limy members in the section and allowed a collapse structure to form just as would happen if a portion of the foundation were to be removed from beneath a brick wall.

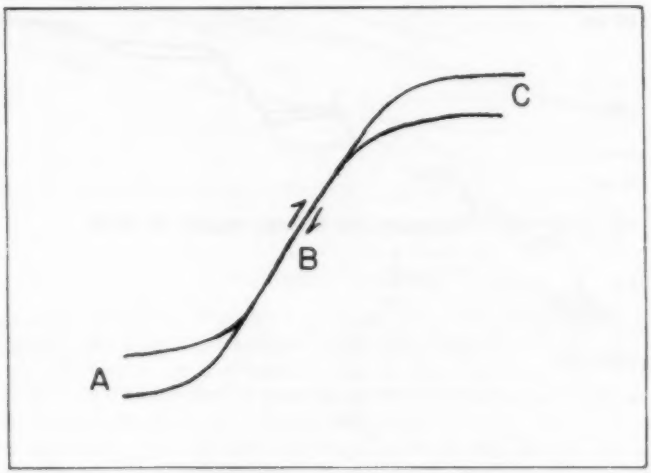

FIG. 8.

Heyl and others have advocated the theory that pitches formed by thrust faulting, beginning as bedding plane faults at the claybed, then curving gently upward to about 45° and then turning gradually back to the horizontal at any place from the top of the Gray to 50 feet up into the Drab member, where it again becomes a bedding plane fault. At the relatively shallow depths this deformation took place, the Drab and Gray, and to a lesser extent the Blue, must have acted as competent beds. Figure 8 illustrates the case of a thrust fault under such conditions.

Analyzing Figure 8 the displacement at A and C should be equal or nearly so and the fault plane at B would be very tight and probably effectively sealed with gouge. The writer cannot reconcile this conception of a pitch structure with his observations. First, displacement on any pitch is a maximum at A

(Fig. 8) and becomes progressively less with height on the structure. Second, the pitch at B (Fig. 8) is never tight or gouge filled. Crustification banding of the ore and large open vugs show clearly that mineralization occurred in an open fissure, sometimes as much as several feet in width.

Figure 9 shows an actual pitch as mapped in the South Hayden orebody that illustrates the points brought out above as criticism of the thrust hypothesis for the origin of the pitch structure.

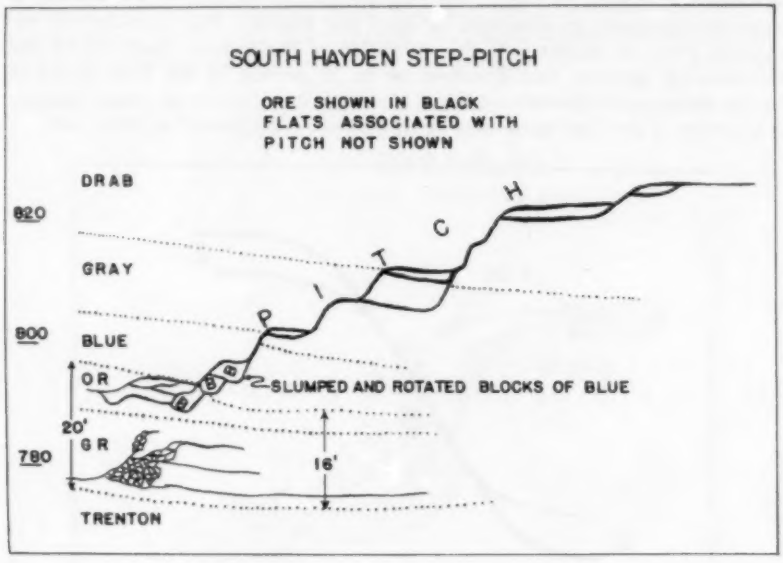

FIG. 9.

Tectonic Origin of Pitch Fractures

Figure 10 shows the suggested mechanism by which the fracturing originated on the flanks of the folds, and the manner in which the pitch utilized these fractures in the development of a step-pitch structure such as exemplified by Figure 9. The linear east-west or northwest orebodies almost invariably show pitches of this type.

The arcuate pitch orebodies generally occur around plunging synclines, roughly following a contour around the fold. Rarely an arcuate pitch will circle the end of a plunging anticline in the same manner. It is thought that the additional warping of the folds has produced an arcuate zone of tension fractures by the same mechanism outlined above that may be more intense through a wider vertical range. This arcuate tension fracture zone when exposed to mineralizing solutions will often develop into the smooth wall type of pitch due to solution and collapse of the footwall.

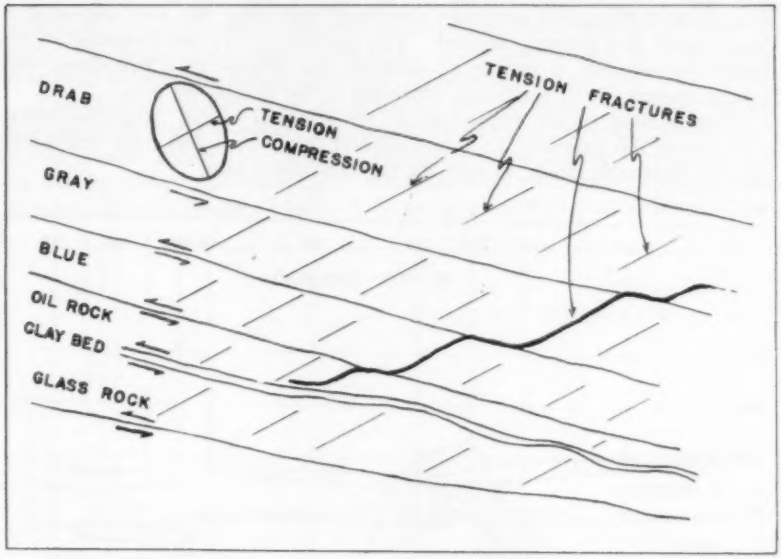

FIG. 10.

Pecatonica Anticlines

The cross-sections in Figure 11 are derived from drill hole data, the solid lines marking the tops of the various members as logged. In all cases sections were selected where ore is present in the Mifflin member of the "Trenton." Also in all cases where ore is present in the Mifflin, an anticline is located directly underneath at the top of the Pecatonica.

Due to thinning of the limy Mifflin, Glassrock and Oilrock members by solution, evidence of the Pecatonica anticline is seldom reflected in these formations.

The mode of origin of this singular structure, I believe, is intimately tied in with the development of the ore receptacle. As solution of the limy members overlying the Pecatonica continued, tectonic stresses acted from time to time on the Pecatonica causing it to buckle upward into the zone undergoing solution above. This would represent a relief of lateral forces while at the same time exerting vertical pressure on the limestones, and also perhaps promoting solution of these members.

The Role of Solution in the Formation of the Ore Receptacle

In the section on stratigraphy the relation of ore deposits to the degree of solutional thinning was briefly discussed. The role of tectonics in the forma-

tion of the folding and necessary attendant fracturing was also discussed at some length in a previous section. The explanation for the formation of the fracturing required to initiate an orebody was offered as a hypothesis that seemed to best fit the conditions obtaining in the Shullsburg area.

The relation of ore deposition to the solution of the Magnolia-Mifflin members of the Trenton, the Glassrock and the Oilrock has been established beyond reasonable doubt, at least for the Shullsburg area.

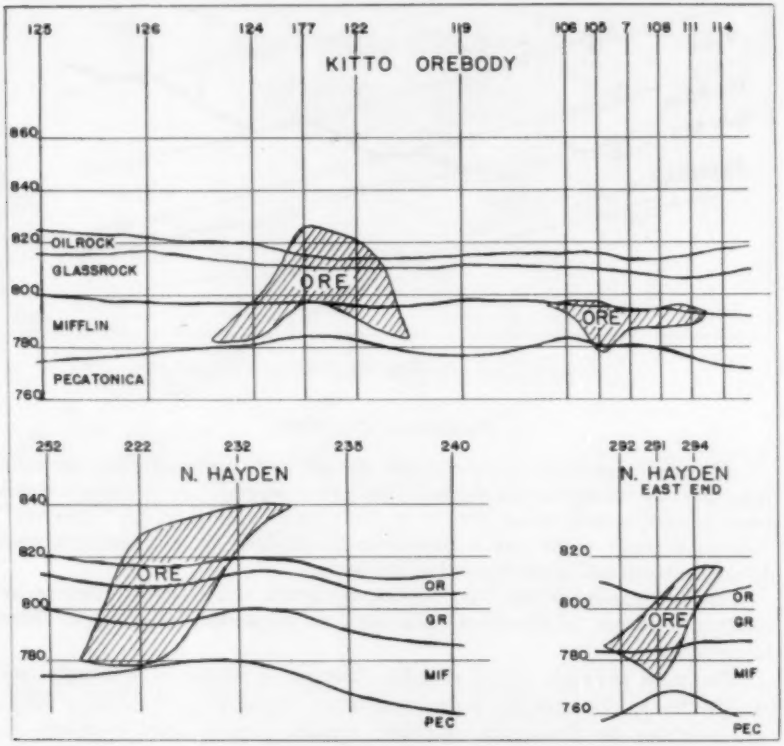

FIG. 11.

The major "bottom run" orebodies will be classified into three distinct types of deposits, as follows: 1) pitch and flat runs, 2) Glassrock runs, and 3) Trenton runs. All of these "bottom run" types may occur singly, any combination of two, or all three together. The degree of thinning of the members involved has determined the type of deposit that resulted.

Figure 12 shows the influence of solutional thinning of the Oilrock and Glassrock members on the type and thickness of the deposit. Orebodies con-

taining significant amounts of Trenton ore were omitted because they only confuse the issue. Trenton ore requires only solutional softening and thinning within this member and may often occur where the Oilrock and Glassrock have been so little affected as to exclude deposition of higher ore.

The Gensler orebody is an example of a well developed pitch-flat deposit throughout its length combined with an extensive Glassrock run. Trenton ore in this deposit occurs only locally. From the curve it should be noted that the average amount of thinning of the Oilrock-Trenton interval (maximum thickness 30 feet) is over 12 feet and the average ore thickness is about 50 feet.

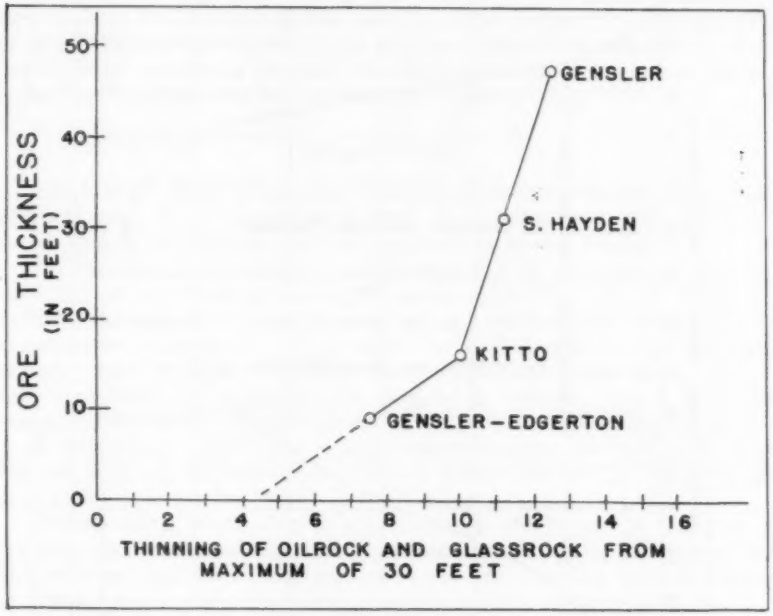

FIG. 12. Data taken only from drill holes on the various orebodies represented.

The South Hayden orebody is a more complex deposit than the Gensler as it contains, in various parts of its lateral extent, all possible combinations of "bottom run" ore deposition. However, Trenton ore forms only a very small percent of the total. Pitch-flat ore makes up a substantial portion of this deposit as might be expected from the degree of thinning of the Oilrock and Glassrock.

The Kitto orebody has only a very limited pitch-flat run near its center, either end being composed entirely of Glassrock and Trenton ore. As anticipated, the curve shows that the amount of Oilrock and Glassrock thinning is less than either of the above deposits and that the ore thickness is correspondingly less.

The Gensler-Edgerton orebody represents the simplest possible case as only one type (Glassrock) ore is involved. The average thinning of the Oilrock and Glassrock is less than 8 feet for this deposit and the average ore thickness is only 9 feet.

An average curve constructed by plotting all ore holes on the same basis as Figure 8 shows the same clear-cut relationship between thinning of the Oilrock and Glassrock and ore thickness.

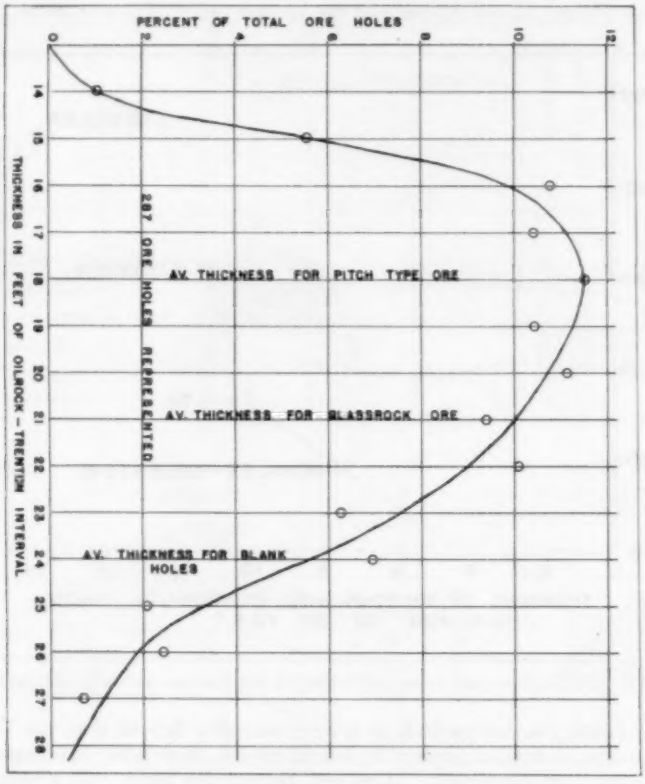
PERCENT OF TOTAL ORE HOLES
THICKNESS IN FEET OF OILROCK-TRENTON INTERVAL
287 ORE HOLES REPRESENTED
AV. THICKNESS FOR PITCH TYPE ORE
AV. THICKNESS FOR GLASSROCK ORE
AV. THICKNESS FOR BLANK HOLES

FIG. 13.

Over 1,000 drill holes in the Shullsburg area were used to determine the average Oilrock-Trenton interval for the two most important types of deposits: 1) pitch-flat runs and 2) Glassrock runs. Figure 13 shows that pitch-flat type receptacles require extensive thinning of the Oilrock and Glassrock or an average thickness of 18 feet. The figure also shows that if less thinning has been involved (average interval 21 feet) the result will be Glass-

rock runs only. An average of the 700 plus blank holes showed an Oilrock-Trenton interval of 24 feet. This average of 24 feet for blank holes would have been raised to at least 25 or 26 feet had it been possible to omit the many blank holes that were near misses and within the zone of alteration and thinning.

The special case of Trenton run ore has been described briefly in a previous section and a hypothesis advanced for the origin of the peculiar Pecatonica anticline it appears to be associated with. Only one more fact should be re-emphasized in connection with Trenton run ore and that is there need be little or no thinning of the overlying Glassrock and Oilrock. However, if ore does occur in the Magnolia-Mifflin member of the Trenton, this member will be greatly thinned and "softened" by solution. As there is seldom a marked depression or elevation at the top of the Magnolia-Mifflin, the logical conclusion is that the Pecatonica has been arched from beneath.

GUIDES TO ORE

All of the preceding information is not only of academic interest but also has practical use. The following suggestions for exploration within the Wisconsin-Illinois district have been tried and found to be very helpful.

1. *Structure.*—The drilling of widely spaced N–S cross-sections may be used to great advantage in locating the structurally low areas for follow up drilling. In this manner over 50 percent of a potential area may be eliminated. A satisfactory hole spacing was found to be N–S cross-sections on 660-foot centers (chosen to fit the land subdivision) and spaced ½ mile apart. Structure is of minor importance in following up an orebody, once it is found, because of the complexity and subtility of the structure controlling the ore.

2. *Alteration.*—The degree of solutional thinning of the Oilrock-Trenton interval is of utmost importance and may extend beyond the limits of an orebody for some distance, particularly on strike.

Dolomitization of the Oilrock and Glassrock should also be noted as it is commonly present over the same general areas that are affected by solution. It is of lesser importance than solution; however, because it is much harder to detect.

It should also be noted here that outside of the mineralized area the Oilrock and Glassrock are commonly dolomitic. Where this (primary dolomite) condition exists it is virtually useless to look for "lower run" deposits.

3. *Mineralization.*—Though listed last, this is at least on a par with structure and alteration as a guide to ore.

The presence of fine marcasite in some quantity in a drill hole is of considerable diagnostic value. This fine marcasite appears rather early in the paragenesis, contemporaneous with sphalerite, and is commonly deposited in alternating crustified bands with sphalerite in the open fissure-type veins. This fine marcasite is easily recognized as it colors the drill water and sludge black. Whenever this condition occurs the drill is almost invariably near sphalerite mineralization.

Not to be confused with the fine marcasite is the very late, more coarsely

crystalline marcasite that overlaps the earliest calcite stages in the paragenesis. This coarsely crystalline marcasite, sometimes locally termed "brass," is widely distributed and of scant diagnostic value. Where some sphalerite occurs with the coarse marcasite it imparts little more worth to the area in question than if coarse marcasite alone is present.

Galena, in relatively small deposits, is widespread throughout the district (Fig. 1). As such, it has scant diagnostic value for "lower run" deposits.

All "ore bites" do not prove up to be orebodies in the Wisconsin-Illinois district. The experience gained in Calumet & Hecla's exploration campaign would indicate that an "ore bite" has about one chance in four of developing into an orebody.

CONCLUSIONS

1. Complex minor folding of the district is suggested as being caused by minor faulting and adjustments in the crystalline basement as an alternative to the hypothesis that lateral pressures causing the folding originated at some distance outside of the district.

2. It is also hypothecated that a large magmatic body underlies the district. Probably this magma did not reach the top of the Precambrian crystallines. It is suggested that minor faulting and adjustment occurred in the roof of this pluton. This deep magma is also suggested as the probable source of the mineralizing agencies and the faulting of the basement rocks as the conduits through which these agencies ascended to form orebodies in the Ordovician sediments.

3. Apparent thrust displacements on the pitch structures are due to solution of the limestone members, Oilrock, Glassrock and upper Trenton, causing progressive collapse of the more competent beds above. It has been conclusively shown that the greater the thinning of the limy beds by solution, the thicker the resultant orebody.

4. The location of the ore deposits is controlled by fractures of tectonic origin, but solution and collapse played the dominant role in the formation of the ore receptacle.

5. Ore deposition is largely controlled by the east-west fracture system. Over 90 percent of the ore in the Shullsburg area has an approximately east-west trend.

6. Study of the mineral zoning pattern indicates that ore solutions probably ascended along limited stretches of the east-west fracture zones. Zoning indicates that growth of the receptacle kept pace with mineralization, continuing to grow until the last minerals of the paragenitic sequence were deposited.

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The writer is particularly indebted to T. M. Broderick, Chief Geologist of Calumet and Hecla, retired, under whose direction the Wisconsin exploration program was conducted. Without his encouragement and critical reading of the manuscript, this paper would not have been completed. I also especially wish to acknowledge the very considerable help of H. B. Ewoldt and

R. W. Kliebenstein, who also worked under Dr. Broderick on this program. Our innumerable discussions on problems of exploration served to standardize the procedures outlined above. The writer is also indebted to Allen Heyl and Allen Agnew of the U. S. Geol. Survey and H. B. Willman of the Illinois State Geological Survey for many informative discussions on the district, and to Walter S. White of the U.S.G.S. who critically read the manuscript. Finally, thanks is due Willard C. Lacy of the University of Arizona, who helped in the preparation of this paper for publication

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CERRO DE PASCO CORP.,
TUCSON, ARIZONA,
Sept. 18, 1957

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ALTERATION OF BIOTITE UNDER MESOTHERMAL CONDITIONS

GEORGE M. SCHWARTZ

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ABSTRACT

The complex chemical composition of biotite is doubtless the cause of a variety of alteration products when it has been altered by hydrothermal solutions at moderate temperatures and pressures. As a rule biotite is unstable under hydrothermal conditions and alters to numerous minerals that seem to depend primarily on the composition of the solution at any given point. Common alteration products are green biotite, chlorite, muscovite, sericite, hydromica, kaolinite, and other clay minerals, calcite, epidote-zoisite, leucoxene, rutile, pyrite and other sulfides, and less commonly several other minerals.

A complex of several minerals that have replaced biotite within a single thin section is a common occurrence indicating that equilibrium is not normally attained during hydrothermal alteration. The structure of biotite exerts a strong control on the alteration as shown by the occurrence of two or three minerals in bands parallel to the cleavage of the biotite.

The original composition of biotite has a strong influence on the alteration products but minerals such as calcite retain only oxygen of the original elements.

INTRODUCTION

Biotite has long been known to alter readily under hydrothermal conditions. It commonly is altered to chlorite and this has been generally considered to

be the normal product, as is reasonable in view of the similarity of composition of the two groups. In fact, however, biotite alters to a number of minerals, some with little or no relation to the composition of biotite.

For over a decade the writer has studied hundreds of thin sections of hydrothermally altered rocks in which biotite was a primary mineral but normally subordinate in quantity to the feldspar and quartz in the rock. The complexity of the alteration of biotite was continually observed during these studies.

Recently several hundred thin sections were reexamined with attention centered mostly on biotite and products of its alteration. The thin sections came largely from rocks altered under mesothermal conditions especially from the disseminated type of copper deposits. The monzonite group of rocks is favorable for the study of biotite, because biotite commonly forms phenocrysts or other grains which are easily recognizable by their shape and structure. An important fact is that no matter how severe the alteration, the outlines of the original biotite grains remain and are marked by disseminated leucoxene aggregates or rutile grains. In some respects biotite is a critical mineral in the study of hydrothermal alteration. It is generally one of the first minerals to show the effects of solutions and a wide variety of secondary minerals result. For this reason it deserves detailed study.

Thin sections of hydrothermally altered rocks from the following districts were the principal source of material used in this paper: Ajo, Bingham, Bisbee, Cananea (Mexico), Ely, LaDura (Mexico), Leadville, Miami, Quellaveco and Toquepala, (Peru), Ray, San Manuel, and Santa Rita. A few sections came from various other districts.

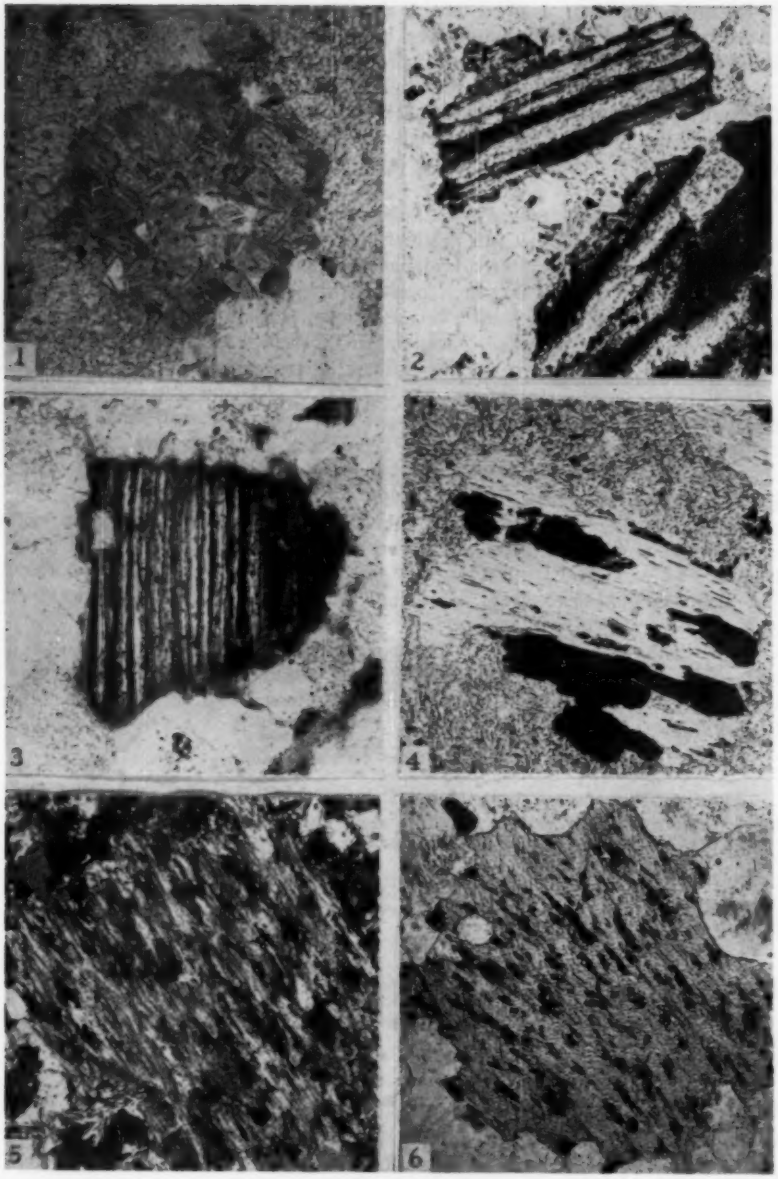
The writer is indebted to his colleagues J. W. Gruner and S. S. Goldich for numerous suggestions. Many of the thin sections were available through work done for the United States Geological Survey and the Phelps Dodge Corporation.

PREVIOUS WORK

The literature on ore deposits and associated hydrothermal alteration contains many incidental descriptions of the alteration of biotite, but there is no published general discussion as far as could be determined. The scattered published data show, as would be expected, that many of the features noted in the present study have been observed by others. The references listed are not intended to be complete but are only those found most useful.

ALTERATION PRODUCTS

Recrystallized Biotite.—It is characteristic of biotite phenocrysts in many porphyries to have recrystallized to aggregates (Fig. 1). These are numerous in the incipient stage of alteration at San Manuel (16) and were observed in thin sections of rocks from several districts. Aggregate pseudomorphs were specifically noted in a total of 43 sections. It seems possible that the recrystallization may be, in part, a deuteric effect but in general their occurrence is so closely allied with minerals of hydrothermal origin that a similar origin



FIGS. 1–6.

seems probable. Several examples were observed of aggregate pseudomorphs altered to a complex of the hydrothermal minerals described below.

Biotite that has formed or recrystallized during hydrothermal alteration does not necessarily form aggregates within original outlines. Anderson (1), for example, describes disseminated leafy biotite in the biotite-albite-quartz-orthoclase alteration facies at Bagdad, Arizona. He noted that the leafy, disseminated biotite was pale in color compared with the primary biotite and that the index of refraction and iron content were lower, and the magnesium content higher than in the primary biotite.

Brown biotite may alter at an early stage to green biotite, which is easily distinguished from the common green chlorite by its high birefringence. The two were observed together in several thin sections. Green biotite was determined in 3 percent of approximately 340 thin sections and it may have escaped notice in others where chlorite and sericite are abundant. In some thin sections there is a well-defined sequence from normal brown biotite, to faded or light-brown, and thence to green biotite, which in turn is altered to green chlorite.

Several writers have emphasized the gradual transition of biotite to pale biotite, thence to chlorite. For example, Kerr (6, p. 318) states that at Santa Rita, as alteration progressed the biotite exchanged its deep absorption for a pale olive-brown or reddish-brown pleochroism.

Muscovite.—In discussing the alteration of biotite the problem of nomenclature arises. Sericite is usually classed as a variety of muscovite and normally occurs as fine flakes or shreds. Winchell (18, p. 369) defines it as follows: "sericite is a fine scaly or fibrous kind of muscovite. The name is usually confined to white mica that is secondary." Wright and Shulhof (19) recently used a diameter of 0.25 mm as the basis of differentiation between sericite and muscovite.

In describing the alteration of biotite it is necessary to distinguish two kinds of secondary muscovite. The first variety consists of perfect, or nearly perfect, pseudomorphs of colorless mica after biotite and for the present purpose is conveniently called secondary muscovite. Less common in altered biotite is the fine flaky, or fibrous variety that is called sericite. It should be emphasized that in the alteration of feldspar and minerals other than biotite the flaky or fibrous variety, sericite, is formed almost exclusively, whereas more commonly single crystals of muscovite (Figs. 4, 11) are developed as pseudomorphs after biotite.

FIG. 1. Recrystallized biotite phenocryst or aggregate structure. San Manuel, Ariz. Plane polarized light. × 36.

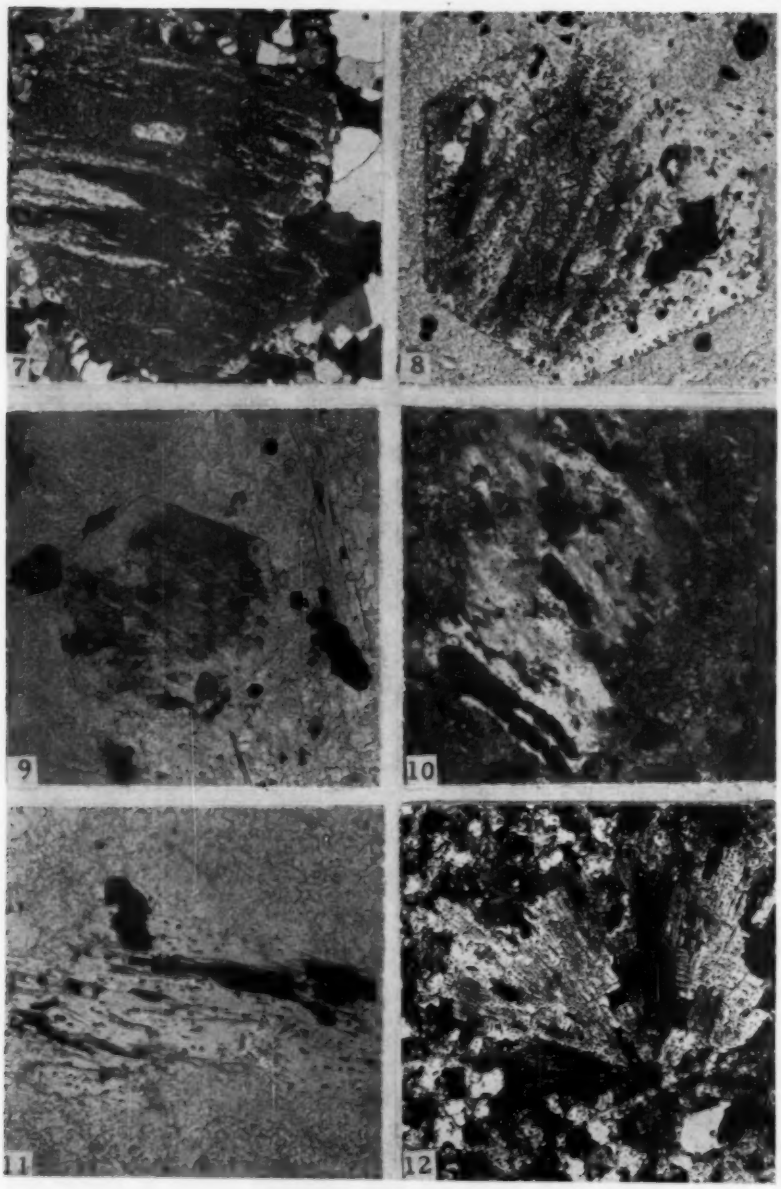
FIG. 2. Calcite lenses (white) in biotite (dark). San Manuel, Ariz. × 65.

FIG. 3. Interleaved muscovite (light) in biotite (dark). Bisbee, Ariz. Plane polarized light. × 90.

FIG. 4. Pseudomorph of muscovite after biotite. Small inclusions are rutile, black grains are pyrite. Morenci, Ariz. Plane polarized light. × 90.

FIG. 5. Biotite phenocryst which has altered to shred-like sericite. Dark inclusions are leucoxene. Morenci, Ariz. Plane polarized light. × 115.

FIG. 6. Biotite grain which has been completely altered to chlorite and leucoxene. Plane polarized light. × 90. Ajo, Ariz.



FIGS. 7–12.

The formation of complete pseudomorphs of secondary muscovite, which under crossed nicols extinguish as a unit, is characteristic of fairly intense alteration (Fig. 4). Of the 340 thin sections studied in detail 96 contained muscovite pseudomorphs of varying perfection. The pseudomorphs are never pure muscovite but invariably contain inclusions of leucoxene or rutile. Less commonly other minerals such as pyrite, calcite, and epidote, occur within the pseudomorphs. The muscovite pseudomorphs are naturally numerous where sericitization of the rock is intense and they are generally lacking where chloritization is predominant, as at Ajo, Arizona. The intensely altered rocks of the ore body at Morenci, Arizona, show muscovite pseudomorphs in more than half of the available thin sections. The alteration of biotite to muscovite was noted as early as 1897 by Lindgren (9) who makes the following statement in describing the alteration of the country rock in the Idaho basin: "there are a few larger muscovite foils, which evidently represent the biotite of the fresh rock."

Sericite.—If the term sericite is limited to the fine shreddy or flaky variety of secondary potash mica it is not nearly as abundant as the unit pseudomorph replacement by muscovite. Sericite is, however, abundant in the altered feldspar of most of the thin sections. This points to the fact that unit pseudomorphs of secondary muscovite are characteristic of biotite and shreddy sericite of feldspar.

As previously noted, recrystallization may develop shred-like sericite around the edges of secondary muscovite flakes. In studying the published papers, it is not always possible to distinguish secondary muscovite from sericite as the terms are used in this account. There are a number of references to biotite altered to sericite; however, in some descriptions hints occur of what Sales and Meyer (14) term unit pseudomorphs. Thus Kerr (5) states that in stage 4 alteration at Silver Bell, Arizona, biotite altered to sericite or shows only relict outlines. Farther along, however, he describes biotite as having turned white thus suggesting secondary muscovite or unit pseudomorphs.

Chlorite.—The alteration of biotite to chlorite is a characteristic feature of hydrothermal alteration and there are many descriptions in the literature of this change. Some of the more recent examples are given by Gilluly (4), Leroy (8), and Schwartz (16). Earlier Boutwell (2) and Lindgren (10) gave good descriptions.

FIG. 7. Biotite (dark stippled) with lenses of chlorite (black) and calcite (light). San Manuel, Ariz. Crossed nicols. × 35.

FIG. 8. Pseudomorph of chlorite (dark) and kaolinite after biotite. Black is pyrite. San Manuel, Ariz. Small black specks are rutile. × 279.

FIG. 9. Hexagonal biotite phenocryst which has altered to epidote in the center and chlorite at the edge. Dark spots in the crystal are leucoxene. Black grains outside are pyrite. Bisbee, Ariz. Crossed nicols. × 90.

FIG. 10. Pseudomorph of kaolinite plus pyrite after biotite. Crossed nicols. Morenci, Ariz. × 65.

FIG. 11. Pseudomorph of muscovite after biotite. Small inclusions are rutile, black grains are bornite and chalcocite. Miami, Ariz. Plane polarized light. × 90.

FIG. 12. Radiating aggregate of tourmaline in a former biotite area. Cananea, Mex. Crossed nicols. × 90.

The alteration of biotite to chlorite has frequently been assigned to an early stage, or marginal type of alteration and this is partly true. In general the present investigation has not revealed much evidence of chlorite in turn altering to later minerals. Recognizable remnants of chlorite in later minerals seems largely lacking and suggest that once formed, chlorite is a relatively stable mineral under hydrothermal conditions. Of the thin sections examined during this investigation about 40 percent contained chlorite. In the rocks from the New Cornelia Mine at Ajo, both ore and wall rock contain chlorite. At Morenci, on the contrary, most available thin sections show no chlorite.

Complete pseudomorphs of chlorite after biotite (Fig. 6) are common but partial alteration is naturally more abundant. Interleaved lenses of chlorite and calcite (Fig. 7) are present in many grains. Ransome (13) long ago observed lenses of chlorite with interlamellar grains or plates of calcite and epidote in monzonite porphyry from Breckenridge, Colorado. Other complex associations include epidote in the center surrounded by a border of chlorite (Fig. 9). In a thin section of rock from the San Manuel district, Arizona, chlorite forms the center of a pseudomorph and kaolinite the outer part (Fig. 8).

The chlorite that is the common product of alteration of biotite is bright green in plane polarized light and has a very low, ultrablue interference color, which corresponds to the variety pennine. In a few thin sections both pennine and chlinochlore were observed within the outline of a single biotite crystal.

Epidote-Zoisite.—Epidote is a sparse alteration product of biotite; it was recognized in 17 of 339 thin sections. Clinozoisite occurred in only one section. In view of the iron available in most biotite it is not surprising that epidote is much more common than clinozoisite.

Epidote was not observed as complete pseudomorphs after biotite but characteristically occurs as grains and clusters of grains in chlorite that is pseudomorphous after biotite (Fig. 9). Carbonate also occurs with epidote at places, thus emphasizing the availability of calcium in the hydrothermal solution. The assemblage chlorite, epidote, calcite is characteristic of the so-called propylitic alteration, which is a marginal or border-zone type of alteration in some districts. This is evidently the situation in which epidote has been found to occur as a product of the alteration of biotite.

Carbonate.—Calcite and closely related carbonates are fairly common as alteration products of biotite. It was observed that in many thin sections carbonate shows a preference for the biotite grains. This suggests that the carbonate may be dolomite, but acid tests show that calcite is common. At Ajo, for example, many altered porphyry samples were tested on sawed surfaces with cold dilute hydrochloric acid and every specimen effervesced vigorously. Carbonate is characteristic of the marginal type of alteration and is commonly associated with chlorite. It is relatively rare in sections that show intense potassic or argillic alteration. For example, of 60 thin sections of ore and protore from Morenci calcite was not recognized in a single section. A characteristic feature is the tendency for carbonate aggregates to occur as lenses or parallel bands in phenocrysts with unaltered biotite, chlorite, muscovite, etc. (Figs. 2, 7).

The fact that carbonate is not readily formed from biotite is shown by thin sections in which hornblende has been extensively replaced by carbonate, whereas biotite in the same section contains little or no carbonate but has been altered to muscovite and chlorite.

Clay Minerals.—Only in recent years has the fact that biotite alters to clay minerals been recognized, although its composition is such that clay minerals are a natural result of alteration when potassium is removed. In distinguishing the various clay minerals Lovering's chart (12, Fig. 12) has been used as a guide. N. H. Fisher (3b) notes that J. D. H. Donnay described biotite from the Wan-Edie Creek area of New Guinea as completely altered to anauxite. The anauxite forms silvery-white pseudomorphs after biotite, which Donnay considered to have developed by way of chlorite. Lovering (11) describes argillized biotite noting that beidellite and dickite partly replaced some biotite crystals in the walls of tungsten veins, and very close to the vein the crystals were largely altered to dickite. He also described biotite as altered to kaolinite and dickite in the East Tintic district (12). Kerr and Green (7) describe pseudomorphs of illite (hydromica) after biotite at Marysvale, Utah. Earlier Kerr and coworkers (6) had found hydromica as a product of the alteration of biotite at Santa Rita, New Mexico. Later Leroy (8) described kaolinite after biotite in the same district. At Butte the alteration is complex as noted by Sales and Meyer (14). In the kaolinite subzone chlorite is changed back to biotite.

In the present work biotite was observed altered to clay minerals in, at least, 50 thin sections. Kaolinite is the most common hydrothermal clay mineral (Fig. 8, 10) but hydromica and nontronite were also identified in rocks with pyrite and other minerals, which indicate the absence of weathering effects. There is little doubt that a gradation exists from biotite to kaolinite. For example, in a thin section of rock from the pit at Morenci, Arizona, biotite has altered to pseudomorphs of muscovite which then grade, as shown by a fading birefringence, through hydromica to kaolinite. At one place in the thin section three biotite grains have largely been altered to muscovite, but at one end a grain has hydromica between sericite and kaolinite. In another thin-section from the same mine green biotite fades within a single crystal to colorless muscovite. In other grains muscovite is mixed with green nontronite. Several pseudomorphs in the Morenci thin sections consist of a mixture of kaolinite, halloysite and allophane. Beidellite was also identified in one section. It is probable that practically all species of clay minerals are present in the intensely argillized porphyry at Morenci and doubtless all could be found as a product of the alteration of biotite.

Another thin section of a Morenci rock subjected to extreme argillization contains clay pseudomorphs after the feldspar phenocrysts, together with complex pseudomorphs after biotite. The latter contain abundant disseminated leucoxene in a clay complex that consists of numerous parallel shreds of hydromica accompanied by several minute nests or aggregates of extremely fine-grained kaolinite, which is at places brownish in transmitted light on account of the presence of isotropic allophane. Small grains of quartz are irregularly distributed in the former biotite areas.

The extremely fine-grained mixture of clay minerals, particularly in the Morenci ores makes it impossible to separate them for detailed study. One of the troublesome problems was to distinguish between unit pseudomorphs of hydromica and kaolinite. Some have a birefringence that results in a first-order yellow, others are first-order gray of varying intensity. Similar relations were noted in thin sections of some of the cuttings from the San Manuel drilling.

A thin section of a porphyry from Bisbee, Arizona contains complete pseudomorphs of a weakly birefringent clay mineral that has a granular texture with the outlines of the original biotite grains. The interference colors range from first order gray to white and from gray to light yellow in other grains. Normal fine-grained kaolinite occurs in the groundmass. The pseudomorphs are believed to be hydromica or potash clay as the term is used by Lovering, (12, Fig. 12). Some of the clay in the Morenci ore described above may also correspond to potash clay.

Leucoxene and Rutile.—One of the most characteristic features of the alteration of biotite is the release of titanium from the biotite which then forms aggregates of white translucent leucoxene or crystals of rutile. Investigation by x-ray methods show that leucoxene is generally a very finely crystalline variety rutile. There is, however, a striking difference between the appearance of extremely fine-grained, earthy leucoxene and the visibly crystalline rutile developed during the hydrothermal alteration of biotite. In a few thin sections earthy leucoxene and extremely fine-grained, but visibly crystalline rutile were mixed in aggregates, which indicate enough recrystallization to render the grains transparent and birefringent. This occurrence of leucoxene and rutile is useful because it makes identification of former biotite areas possible at a glance. The general distribution of either, or both, leucoxene and rutile throughout the area of altered biotite is so uniform (Fig. 6) and their practically complete absence in adjacent areas makes this criterion dependable as far as the present investigation could determine.

The elimination of titanium from biotite takes place at an early stage in alteration as the products occur in recrystallized, or aggregate biotite and persists in all of the alteration products. The relation of leucoxene and rutile is puzzling but, in general, it was found that leucoxene is abundant in the less intensely altered rocks and rutile in the most intensely altered. A few thin-sections, however, contain both in a single altered biotite grain. Leucoxene and chlorite are common associates, whereas chlorite and rutile are not. Intensely sericitized rocks normally contain only rutile. Sphene does occur in altered biotite but is rare.

In a few thin sections there is sagenetic rutile and a later hydrothermal generation of either leucoxene or rutile crystals. Where alteration to sericite is far advanced in porphyry as in some of the Apex drilling in the San Manuel district, biotite has been almost completely altered to muscovite or sericite plus pyrite and rutile. In such specimens leucoxene has largely disappeared and rutile is present in all thin sections. In a few thin sections examination at high magnification led to the conclusion that incipient crystallization of

translucent leucoxene to transparent yellow rutile had begun in the late stage of alteration.

Sulfides.—It has long been known that pyrite tends to occur in altered biotite areas, and it has been suggested that sulfur combines with iron from the biotite. Enough examples of sulfides (pyrite and less commonly chalcopyrite, bornite, chalcocite) in altered biotite were seen in the present study to indicate that pyrite has a preference for biotite grains in the rocks of some districts (Figs. 4, 8, 9, 10). In general, however, sulfide is not abundant in former biotite areas even though a high percentage of the thin sections examined contained sulfides. Sulfides clearly replaced biotite in at least 62 of the nearly 400 thin sections examined.

Biotite represents a stable mineral in some of the less common examples of sulfide mineralization. At Bingham the so-called "dark" porphyry has abundant shreds and flakes of biotite in addition to phenocrysts. Some of the phenocrysts have recrystallized to aggregate biotite. In one exceptionally good example pyrite was abundant in such an aggregate which, judging from its shape, was originally one biotite flake.

Quartz.—One of the noteworthy features of the alteration of biotite in the specimens examined by the writer is the small amount of quartz as an alteration product of biotite. Introduced quartz within a former biotite area was rarely observed although the presence of quartz replacement veins in some ores make it probable that biotite, as well as all other minerals in the porphyry were replaced. Examination of the pseudomorphs after biotite at high magnifications occasionally shows scattered quartz grains. These are not necessarily all of hydrothermal origin but many doubtless are, particularly where an original single biotite crystal is involved.

Lesser Minerals.—It is to be expected that various alteration products would replace biotite to a limited extent, but in general the writer found surprisingly few exotic minerals. In the zone of intense alteration at San Manuel kaolinite and alunite are abundant, and alunite was observed in former biotite areas. Magnetite was observed in only a few thin sections as an alteration product of biotite. This is because the iron in many hydrothermally altered porphyries tends to form pyrite. In one thin section of highly altered rock from Morenci a green flaky nontronite occurred with muscovite, sericite, leucoxene, pyrite, and chalcocite. An unusual occurrence is that of biotite partly replaced by tourmaline in a rock from Cananea, Mexico (Fig. 12). The thin section shows that other biotite grains have altered to sericite, kaolinite and rutile.

Samoyloff (14b) describes biotite altered to tourmaline or tourmaline-quartz aggregates, or to muscovite in a deposit that shows a gradation from pneumatolytic to hydrothermal conditions.

Apatite crystals occur within biotite but these are primary inclusions. In one thin section apatite appears to have altered to calcite. Sphene was noted in biotite but normally this also is believed to be a primary mineral but it is possible that in exceptional occurrences sphene may have formed during hydrothermal alteration. Lindgren and Ransome (9b) noted that adularia replaced biotite at Cripple Creek, also roscoelite and an unknown mica.

COMPLEX ALTERATION

Because of its complex chemical composition and the variability of both the composition and temperature of hydrothermal solutions it is common to find rather striking combinations of alteration products. A few examples are given to illustrate this point.

In a porphyry from Bisbee, Arizona, single pseudomorphs after biotite contain a central zone of epidote, a rim of chlorite and disseminated leucoxene and pyrite. Another pseudomorph in the same thin section is composed of muscovite plus leucoxene. In other thin sections of rocks from the same district single pseudomorphs consist of sericite, kaolinite, leucoxene and pyrite. Another even more complex association was observed in a single pseudomorph that consists partly of secondary muscovite, patches of fine-grained shreddy sericite, and intergrown chlorite, clinozoisite, quartz and sphene. Although pyrite is abundant in this thin section none occurs in the pseudomorph.

The copper deposit at San Manuel, Arizona (16) has four well-defined types of alteration, more or less zoned. The alteration of biotite is variable with the location. In hole 9 located in the hydromica-pyrite type of alteration at a depth of 650 feet thin sections show hexagonal-shaped pseudomorphs after sagenetic biotite which consist of a central zone of chlorite fading outward to kaolinite with pyrite and rutile inclusions. Muscovite pseudomorphs after biotite occur in the same section.

Thin sections from a depth of 700 feet in hole 11 at San Manuel which is also located in the pyrite-hydromica zone contain biotite in various stages of alteration to chlorite, muscovite, hydromica, kaolinite, pyrite and leucoxene.

A thin section of monzonite porphyry from a depth of 865 feet in hole H contains deformed biotite phenocrysts that display a complex interlayering of brown and green biotite, chlorite and calcite. Where alteration is more advanced remnants of brown biotite remain in green biotite and in chlorite.

A thin section from hole 45 at a depth of 755 feet contains primary brown biotite remnants, recrystallized aggregate biotite, green biotite, chlorite, calcite, leucoxene, rutile and magnetite.

In hole 48 at 950 feet a complex of brown and green biotite, chlorite, and calcite occur in a single thin section. Some pseudomorphs after biotite contain more than half calcite plus green biotite remnants and chlorite lenses in parallel intergrowth with calcite. Pale brown biotite and green biotite remnants occur in the same pseudomorph. A peculiar occurrence in the same section is a uniform green pseudomorph, which under polarized light proves to have a fringe of green biotite around the core of chlorite.

In a dark porphyry from the New Cornelia Mine at Ajo, Arizona, biotite has altered to chlorite, sericite, epidote, hydromica, calcite, leucoxene, and rutile, plus chalcopyrite and bornite in some pseudomorphs.

SPECIAL FEATURES

Some of the features noted during the examination of thin sections deserve detailed description and comment. The structure of biotite obviously exerts

a strong control over the replacement by alteration products. There is a marked tendency for alteration to proceed along distinct zones parallel to the cleavage of the biotite phenocrysts. Thus, as previously noted, biotite remnants and the green biotite, chlorite, muscovite, calcite, and less commonly other alteration products tend to occur as minute alternating layers (Fig. 3).

Even more striking are the lenses of carbonate which occur in many altered biotite phenocrysts (Figs. 2, 7). These are characteristically lens-shaped rather than plate-like. Why this should be is not evident, but it may be that it is caused by the growth of the lenses by crystallization inasmuch as the carbonate, especially calcite, chemically is unrelated to the original biotite.

In a few sections areas of calcite within a biotite crystal clearly distort the cleavage of the crystal without notably changing the outlines of the crystal. There seems little doubt that the crystallization of the calcite forced the cleavage plates of biotite apart, and the result is a structure much like the augen structure of some schists. The crystals as a whole were little distorted suggesting partial replacement and partial growth by expansion.

Sulfides commonly tend to form elongated masses parallel to the cleavage (Figs. 4, 10) but these are much less clear-cut than those of chlorite, calcite, and muscovite.

A puzzling feature in some grains is that residual biotite persists around the border of the pseudomorph whereas all of the remainder was altered to chlorite or other minerals.

DISCUSSION

Biotite is a complex isomorphous mixture as is evident from the newer formulas assigned to it, for example the following is given by Winchell (18, p. 373):

$$K_2(OH)_4(Mg, Fe, Al)_6(Si, Al)_8O_{20}$$

Substitutions are common in biotite and some to be expected are sodium, rubidium, cesium, barium, and calcium substituting for potassium, lithium, chromium, vanadium, and titanium for magnesium, and fluorine and chlorine for the hydroxyl.

There are possibilities for a variety of alteration products. The presence of ferrous iron in biotite is a factor in the relative ease of alteration under hydrothermal conditions because most silicates containing iron are altered by H_2S.

Biotite in rare occurrences is stable in the presence of mineralizing solutions, as has been emphasized by Sales and Meyer (14). Other examples of stable biotite or its formation by hydrothermal solutions were observed by the writer in specimens from Bingham, Ely, and Santa Rita.

In a thin section of intensely altered rock from the San Manuel district part of the biotite is essentially unaltered, some aggregates range from brown to colorless but the feldspar is highly altered to a light-green clay which gives a kaolinite x-ray pattern.

The solutions have commonly leached iron and magnesium and substituted potassium as shown by the abundance of secondary muscovite and sericite,

pseudomorphous after biotite. Where chlorite is the abundant product as, for example, in many parts of the New Cornelia Mine at Ajo, potassium was removed from the biotite, although Gilluly's (4) analyses show that potash has increased in the altered rock as compared with much less altered samples.

In the discussion of biotite it is desirable to distinguish between alteration that may be defined as the formation of new minerals by utilizing part of the original elements, as the alteration of biotite to muscovite or chlorite, and replacement where the original material is completely removed and new elements introduced as in the alteration of biotite to calcite.

The study of the hydrothermal alteration of biotite shows that equilibrium is rarely reached during the process. It is not difficult to find several minerals formed from biotite within a single thin section or even within the outline of a single small phenocryst. This indicates that not pressure or temperature but composition of the hydrothermal solution is the dominant factor.

Another significant fact shown is that permeability of the rock is extremely variable because one grain of biotite may be largely altered and another in the same thin section remain untouched. Diffusion, except where the solution is able to penetrate the rock very intimately, does not appear to be important.

It is probable that no single sequence exists, nevertheless, there are minerals that appear in some sequence in a number of thin sections. Recrystallized biotite is always the earliest effect when present and, may be deuteric in some if not all examples. The change from brown to green biotite follows recrystallization and is in turn commonly followed by chlorite.

The early release of titanium results in leucoxene, but in the more intensely altered rocks this normally has recrystallized to rutile.

Unit muscovite pseudomorphs seem to form directly from biotite, bleached or recrystallized biotite. Sericite, however, was observed as veinlets cutting across kaolinite. Muscovite pseudomorphs in the more intensely sericitized rocks is frequently frayed at the border thus, in effect giving a transition to sericite.

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CHEMICAL CHARACTER OF WATER IN THE IGNEOUS AND METAMORPHIC ROCKS OF NORTH CAROLINA[1]

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ABSTRACT

The igneous and metamorphic rocks of North Carolina vary considerably in chemical composition and, consequently, in solubility. Each major chemical type yields ground water having a distinctive chemical character; enough contrast generally exists for chemical analyses of ground water to be an aid in geologic mapping where outcrops are scarce.

In their chemical character and that of the water derived from them, the rocks of North Carolina can be divided into two groups. The first includes granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs; these rocks resemble granite in composition. The second group includes diorite, gabbro, hornblende gneiss, and andesite flows and tuffs; these rocks resemble diorite in composition. The granite group yields a soft, slightly acidic water that is low in dissolved mineral constituents; the diorite group yields a hard, slightly alkaline water that is relatively high in dissolved material.

Lithologic determinations based on the chemical character of ground water are generally reliable in regions of similar climate and topography. Anomalies in dissolved mineral constituents that are not due to differences in rock type, climate, or topography may indicate either abnormal structural conditions, resulting in abnormal rates of circulation of the water, or the presence of concentrated mineral deposits.

INTRODUCTION

IN geochemical exploration for mineral deposits, attention is commonly devoted chiefly to the chemical behavior of a specific mineral or suite of minerals. The rapid development of geochemical exploration in recent years justifies a broadening in the scope of studies so that geochemical norms and anomalies in specific rock terranes can be determined; as this is done a base can be formed from which further geochemical studies can aid either directly or indirectly in mineral exploration. A case in point is the evaluation of the chemical character of water in igneous and metamorphic rocks.

For several years the U. S. Geological Survey has been studying the ground-water resources of the igneous and metamorphic rocks of North Carolina. This work has been done in cooperation with the Division of Mineral Resources of the North Carolina Department of Conservation and Development. A part of this study has dealt with the chemical character of the water in these rocks.

The aims of this paper are (1) to show the variations in chemical character of water from the crystalline rocks of North Carolina, (2) to discuss some factors that govern the amounts of soluble constituents in the water, (3) to

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demonstrate how the major chemical types of rocks can be classified according to the water they yield, and (4) to show how the chemical character of the water may be useful in the exploration for minerals. In this paper the common mineral constituents of natural water, those composing more than 99 percent of the dissolved solids, are discussed. Analyses were not made to determine the presence in solution of copper, zinc, and other relatively rare constituents. The analyses were made in the quality-of-water laboratory, of the U. S. Geological Survey, Raleigh, N. C.

SUMMARY OF GEOLOGY AND HYDROLOGY

Igneous and metamorphic rocks underlie both the Piedmont and Blue Ridge provinces of North Carolina. In this paper the Blue Ridge province is considered to include the entire mountainous area of western North Carolina. The easternmost part of the Piedmont province, which includes the central part of the State, is underlain by volcanic rocks, consisting chiefly of slate, in part tuffaceous, and of rhyolitic and andesitic flows and breccias; many of the rocks have the appearance of water-laid deposits and are well layered. West of this belt is an immense series of schists and gneisses and interspaced granite and other plutonic rocks. In aggregate, the igneous and metamorphic rocks trend northeastward and are steeply inclined.

The topography in the Piedmont province is characterized by low, rounded hills and gentle slopes, but to the west the mountainous slopes are longer and steeper. On many mountain slopes, bare rock is exposed, and on others the soil zone is thin. In the Piedmont, however, a heavy layer of residual soil and its veneer of vegetation cap the bedrock in most places. Drainage is facilitated by a close network of perennial streams.

The chemical character of ground water is closely related to its pattern of circulation through the rocks. The natural recharge of ground water occurs on the upland areas and the natural discharge in the intervening valleys. The linear distance between the point where a drop of water first reaches the water table and the point where it is discharged at a spring or seepage area is almost everywhere less than a mile, and commonly less than half a mile.

Water from precipitation infiltrates downward in the residual mantle rock until it reaches the water table. Its movement downward through the pore space of the clay and sand particles is diffused. Upon reaching the bedrock, its circulation is restricted to fractures. Most of the natural circulation is confined to a zone extending no lower than the upper 30 feet of bedrock, because the number and size of water-bearing fractures below that level decrease greatly. Unlike homogeneous and isotropic water-bearing rocks in which water may move at considerable depth below the level to which it ultimately rises to discharge, the consolidated rocks of the Piedmont constrict the downward movement of water and shunt it laterally to springs and seepage areas at or above the base of perennial stream channels. Thus, the movement of ground water from the recharge or interstream areas to the discharge or stream areas generally follows a rather direct path, although locally, of course, water flows through devious interconnecting fractures.

TABLE 1. SELECTED CHEMICAL ANALYSES OF GROUND WATER IN THE IGNEOUS AND METAMORPHIC ROCKS OF NORTH CAROLINA IN PARTS PER MILLION, EXCEPT pH

ANALYSES OF WATER FROM WELLS IN THE PIEDMONT PROVINCE PENETRATING "GRANITE" AND "DIORITE" TYPES OF ROCKS

No.	Location	Owner	Depth in feet	Dissolved solids	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Total hardness as $CaCO_3$	pH	Type of rock	No.
	Alamance County																		
1	Graham	Town of Graham	465	242	33	.26	49	13		11	186	17	21	.0	.8	176	7.55	Greenstone schist	1
2	1 mile S of Mebane	Otis Workman	106	106	38	1.1	12	3.2	6.8	.6	80	.1	8.0	.1	.8	56	6.9	Rhyolite tuff	2
3	Swepsonville	Virginia Mills	408	233	28	.0	32	12		33	177	17	26	.4	.0	129	------	Diorite	3
	Cabarrus County																		
4	Roberta	Roberta Mfg. Co.	275	385	31	.80	33	21		17	146	105	19	.3	1.6	219	------	Gabbro-diorite	4
5	Concord	Clear Spring Farms	170	208	41	.35	56	12		9.8	153	16	12	.2	1.3	139	7.5	Gabbro	5
6	Harrisburg	Lee Clayton	TW	238	36	.06	32	15	28	1.1	203	10	15	.2	2.7	146	6.8	---do----------	6
7	Kannapolis	Ben Aycock	160	88	27	.03	4.3	.0		8.2	26	.9	8.0	.0	.8	14	------	Granite	7
	Caswell County																		
8	Yanceyville	U. S. Defense Plant Corp.	485	344	31	1.3	95	40		61	304	76	85	.0	.3	402	-------	Greenstone	8
	Catawba County																		
9	Catawba	Town of Catawba	285	90	38	.13	8.7	3.6		7.1	53	1.3	8.4	.2	4.0	36	6.8	Granite gneiss	9
10	---do----------	---do----------	360	100	38	.10	7.8	1.9		9.7	38	2.7	4.5	.3	10	27	6.56	---do----------	10
11	Claremont	Town of Claremont	------	120	25	.08	21	4.6		6.4	90	8.6	1.4	.2	.1	71	7.6	Hornblende gneiss	11
12	Conover	Town of Conover	600	120	30	.17	22	5.8		7.6	88	11	8.0	.2	.1	70	7.1	Hornblende gneiss and granite	12
13	---do----------	---do----------	535	106	24	.09	20	3.0		6.8	74	13	1.8	.1	.1	62	6.6	---do----------	13
14	Hickory	Howard Fox	125	86	36	.76	8.6	2.0		11	40	10	1.1	.2	.0	32	7.0	Granite gneiss	14
15	Maiden	Town of Maiden	185	106	32	.06	14	4.2		8	74	3.4	2.6	.1	1.9	52	7.4	Hornblende gneiss	15
	Cleveland County																		
16	Kings Mountain	F. K. Drum	100	89	19	.18	8.6	3.8	3.7	.4	46	1.6	8.0	.2	.0	30	6.5	Muscovite schist	16
17	Lawndale	Cleveland Mill and Power Co.	150	88	14	.21	6.0	2.3		8.3	30	3.4	7.0	.0	7.8	24	5.95	Granite	17
18	---do----------	---do----------	150	123	19	.10	1.8	3.2		13	46	23	17	.0	8.2	68	6.5	---do----------	18
19	Shelby	Dover Mills Co.	165	129	32	.21	28	2.6		7.7	86	13	9.2	.1	.0	81	6.5	Hornblende gneiss	19
	Davidson County																		
20	Lexington	Arcadia School	226	81	36	.11	8.4	1.5		9.6	43	1.3	1.6	.2	1.3	30	6.6	Granite	20
21	---do----------	C. K. Sheets	61	264	32	.29	60	15		16	289	13	28	.1	6.4	211	6.85	Diorite	21
22	3 miles S of Linwood	Colored Church	50	186	33	.04	47	9.6	5.7	2.2	171	2.5	5.5	.0	1.1	134	6.2	Gabbro	22
23	Southmont	Mrs. M. C. Willis	200	278	24	8.7	64	18		18	215	8.5	44	.1	.1	209	7.0	---do----------	23
24	Thomasville	Economy Hosiery Finishers	280	477	21	1.9	64	22		38	106	24	254	.1	.4	328	6.95	Greenstone schist	24
	Forsyth County																		
25	Clemmons	Duke Power Co.	110	71	28	.03	6.7	3.0		1.3	30	3.7	1.8	------	2.2	29	-------	Granite	25
26	3 miles NW of Bethania	Old High School	130	89	31	.02	8.7	3.1		14	42	3.8	1.2	------	.0	37	------	---do----------	26
	Gaston County																		
27	Cherryville	Town of Cherryville	102	111	36	.15	10	4.4		8.3	40	1.9	18	.0	10	43	6.46	---do----------	27
28	---do----------	---do----------	132	107	28	.29	9.2	4.5		6.9	37	2.8	8.4	.0	14	41	6.2	---do----------	28
29	Gastonia	Rex-Hanover Mill, Inc.	267	96	34	1.0	8.5	1.3		10	31	1.3	18	.1	8.1	26	------	---do----------	29
30	North Belmont	Belmont Abbey	340	101	37	.09	12	4.7		6.4	71	1.8	1.8	.1	1.6	48	------	Granite and diorite	30

31	Stanley	Town of Stanley	350	60	21	2.8	3.0	.7		8.0		12	1.1	7.6	.1	7.4	10	8.8	Granite	31
	Guilford County																			
32	Jamestown	Oakdale Cotton Mill	45	108	36	.02	21	6.7		16		80	21	58	------	7.6	80	------	Granite and diorite	32
33	Oak Ridge	Oak Ridge Military Institute	63	63	22	.01	4.0	1.6		6.0		22	2	8	------	2.9	17	------	Granite	33
34	Summerfield	O. S. Miles	271	138	32	.02	23	4.1		18		116	2	2	------	.8	74	------	Granite and diorite	34
	Iredell County																			
35	Barium Springs	Presbyterian Home	60	53	12	.10	1.9	1.1		4.3		12	2.3	2.3	.1	3.6	9	3.75	Granite	35
36	East Monbo	Superior Yarn Mills	415	127	24	5.7	27	7.6		13		132	34	2.6	1.5	.1	124	7.0	Granite gneiss and hornblende gneiss	36
37	Loray	M. J. Hutto	90	60	34	1.5	6.8	2.4		8.6		48	8.7	1.4	.1	.1	27	6.7	Granite and hornblende gneiss	37
38	---do----------	R. D. Murdock	90	25	9.9	.80	1.8	.8		3.5		15	1.2	1.1	.1	.1	8	6.1	Granite	38
39	---do----------	L. W. Stevenson	108	77	31	.06	6.5	2.9		7.6		80	1.6	1.2	.1	.0	28	6.7	Granite gneiss	39
40	Statesville	Carnation Milk Co.	503	178	29	.33	30	7.2		9.1		87	22	21	.1	.1	104	7.5	Hornblende gneiss	40
41	---do----------	Paul Ingram	80	80	31	8.7	5.3	2.7		10		37	15	1.1	.2	.1	24	6.6	Granite	41
42	Troutmans	American Thread Co.	410	65	26	.11	4.6	2.1		6.9		38	1.5	1.5	.1	.2	20	6.6	---do----------	42
43	---do----------	Town of Troutmans	275	84	16	8.3	3.5	1.2	4.2		1.6	25	2.3	1.5	.1	.0	14	6.2	---do----------	43
	Lincoln County																			
44	Cat Square	Dr. Blair Yount	218	92	33	5.5	2.4	1.4		12		26	15	1.2	.1	.0	12	------	Schist	44
45	Lincolnton	Town of Lincolnton	------	67	33	.39	4.7	1.9		5.9		32	3.7	1.6	.2	.8	20	6.8	Granite	45
46	---do----------	---do----------	165	62	29	.17	4.6	1.6		5.8		29	2.7	2.1	.2	.7	18	6.4	---do----------	46
47	---do----------	---do----------	81	70	30	1.8	6.1	2.3		5.8		43	1.3	1.2	.2	.3	25	6.4	---do----------	47
48	Long Shoals	Long Shoals Cotton Mills	129	84	28	.07	8.0	2.5		4.8		34	1.8	1.6	.0	1.7	23	------	Mica schist	48
49	Mariposa	J. G. Morrison	400	123	18	.18	24	3.8		12		115	5.0	2.0	.0	2.2	76	------	Granite and diorite	49
	Mecklenburg County																			
50	Huntersville	Town of Huntersville	148	289	7.1	.07	30	12	6.0		1.6	60	4.2	24	.0	7.7	126	7.2	Gabbro	50
51	Matthews	Town of Matthews	460	130	45	.89	16	5.7		9.8		92	1.9	4.0	.1	.8	63	6.9	Granite and diorite	51
52	Pineville	Town of Pineville	134	305	60	.09	55	26		90		185	94	22	.5	6.0	244	6.7	Gabbro	52
	Rowan County																			
53	8 miles S of Bear Poplar	Mrs. Carl Hall	250	147	39	1.1	18	7.1	5.6		1.2	59	.1	6.4	.0	30	74	6.8	---do----------	53
54	China Grove	Town of China Grove	693	310	22	.04	72	4.1	10		2.8	114	115	6.5	.1	.0	196	7.7	Diorite	54
55	Cleveland	Town of Cleveland	187	260	47	.30	38	16		9.5		127	23	25	.1	22	161	6.8	---do----------	55
56	Cooleemee	T. C. Hendrix	49	191	50	.80	23	11		8.1		87	26	18	.2	5.5	103	8.2	Gabbro-diorite	56
57	Kannapolis	T. H. Powers	161	82	24	.14	4.1	1.5		4.0		24	1.6	2.2	.0	.9	16	6.6	Granite	57
58	Landis	Town of Landis	1108	896	31	.49	174	3.5		15		82	391	2.0	1.8	.2	449	7.3	Diorite	58
59	Rockwell	Town of Rockwell	300	101	22	.04	13	4.8	6.0		.4	73	8.1	3.2	.0	2.0	56	6.9	Diorite and granite	59
60	Salisbury	N. C. State Highway Dept.	290	120	37	.13	15	5.2		3.3		80	9.2	3.6	.0	6.0	84	7.1	Diorite	60
61	Spencer	Town of Spencer	314	90	32	.09	4.6	.6	11		2.0	25	1.1	4.5	.1	9.5	14	6.1	Granite	61
62	---do----------	---do----------	400	227	32	.01	39	15	12		1.8	158	20	14	.2	6.4	126	7.0	Diorite	62

MISCELLANEOUS ANALYSES, INCLUDING 4 (63-66) FROM THE MOUNTAIN AREA AND SOME WITH ANOMOLOUS AMOUNTS OF CERTAIN CONSTITUENTS

No.	Location	Owner	Depth in feet	Dissolved solids	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Total hardness as $CaCO_3$	pH	Type of rock	No.
63	Madison County 7½ miles N of Mars Hill	----------	101	61	22	.24	3.4	1.6		8.7	38	1.1	.9	.1	.2	15	6.9	Granite gneiss	63
64	Macon County Franklin	Town of Franklin	786	32	14	3.8	1.9	1.3		3.3	18	2.0	1.0	.1	1.0	10	5.89	---do----------	64
65	Jackson County Cashiers	H. A. Zachary	63	84	17	.89	4.0	.4		10	34	.6	3.0	.0	2.2	12	6.6	---do----------	65
66	Dillsboro	Town of Dillsboro	338	94	20	.02	14	2.1		10	56	16	3.0	.2	.0	44	7.8	Hornblende gneiss	66
67	Rowan County Gold Hill	John Yelton	65	388	26	23	18	36		11	98	109	29	.1	1.1	193	8.0	Slate	67
68	---do----------	Barnhart Gold Mines	400	------	------	------	------	------		------	70	800	12	------	------	215	7.3	Sulfide zone	68
69	---do----------	----------	----	------	------	------	------	------		------	30	8	182	------	------	81	6.8	---do----------	69
70	---do----------	H. L. Trexler	45	------	------	------	------	------		------	16	18	9.0	------	------	34	6.2	Slate	70
71	---do----------	----------	80	------	------	------	------	------		------	28	1	7.8	------	------	26	6.1	---do----------	71
72	---do----------	Mrs. J. D. Miesenheimer	40	------	------	------	------	------		------	32	8	3.8	------	------	27	6.1	---do----------	72
73	---do----------	C. B. Trent	26	------	------	1.5	------	------		------	22	2.9	16	------	------	20	6.9	---do----------	73
74	---do----------	W. H. Martin	25	------	------	------	------	------		------	72	9	13	------	------	60	7.2	---do----------	74
75	---do----------	C. W. Stancil	65	136	33	2.4	6.0	7.0	15	.8	80	1.6	4.0	.2	.0	32	6.9	Rhyolite tuff	75
76	Cabarrus County Concord	Phoenix Mine	580	427	27	.02	73	26	20	3.0	212	147	6.2	.0	.1	290	7.7	Andesite	76
77	Johnston County Selma	Town of Selma (a)	300	183	36	2.1	16	2.9		7.9	82	13	6.8	.1	.1	58	6.3	Sericite schist	77
		(b)		2160	29	365	180	19	20	5.6	------	1330	16	------	.2	567	8.5		
		(c)		302	34	16	47	9.1	16	2.5	13	186	15	.4	.0	156	5.7		
78	Jackson County Webster	Dr. Roy Kirchberg	250	------	16	.08	2.5	7.7	.2	.0	44	.6	.7	.0	.3	30	8.5	Peridotite	78
79	Iredell County Mooresville	Frank Baker	168	366	30	1.8	62	3.1	6.0	5.1	41	166	8.5	.9	2.8	217	6.9	----------	79

77a analyzed 10/8/53; b analyzed 2/25/53; c analyzed 3/8/54.

ANALYSES OF SELECTED SPRINGS

80	Iredell County Mooresville	S. A. Duckworth	-----	39	15	.04	2.2	.8		4.9	18	.7	2.0	.1	4.0	9	8.8	Granite	80
81	Cleveland County Shelby	T. P. Hamrick	-----	30	11	.09	1.7	.9		3.8	11	1.2	2.2	.1	2.4	8	8.4	---do----------	81
82	Cabarrus County 3 miles SW of Concord	Clear Springs Farm	-----	------	------	------	------	------		------	70	7	------	.3	------	69	6.8	Gabbro	82
83	Gaston County 2 miles N of Lowell	----------	-----	89	23	.21	4.9	2.2		5.3	31	4.3	1.9	.0	.2	21	6.4	Hornblende gneiss	83
84	Davidson County Linwood	Cicero McCrary	-----	99	33	.47	11	4.9		2.8	36	5.0	2.8	.2	6.4	48	6.6	Gabbro	84
85	Lincoln County Lincolnton	James Abernathy	-----	110	17	.26	16	5.4	4.8	1.2	77	9.3	1.8	.1	.5	62	8.8	Amphibolite and granite pegmatite	85
86	Iredell County Turnersburg	Village of Turnersburg	-----	77	17	.99	7.1	3.8		8.8	88	8.7	8.5	.0	8.4	33	6.0	Hornblende gneiss	86
87	Rowan County 8 miles W of Rockwell	O. P. Shuping	-----	96	44	.88	7.8	3.8		7.0	58	1.2	2.2	.3	.2	35	7.1	Diorite and granite	87

The circulation of water in the mountain area is both shorter in distance and quicker in time than that in the Piedmont. This results not from inherent differences in the ability of the rocks to transmit water, but from (a) steeper surface slopes and a steeper water table in the mountains, and (b) the truncation of the water table by many mountain slopes, causing discharge on steep upland surfaces.

Water percolating downward through soil and rock is charged with carbon dioxide, which makes it capable of dissolving some of the soluble minerals, and as the water moves toward a discharge area it does so. As the free carbon dioxide is used up, the solvent power of the water decreases and further solution is retarded. Nevertheless, the amount of dissolved mineral matter in water contained in the rocks increases with time of contact, although this is not a simple, or direct relationship.

CHEMICAL CHARACTER OF THE WATER

The igneous and metamorphic rocks in the southern Appalachians vary considerably in chemical composition, and consequently in solubility. Each major chemical type yields ground water having a distinctive chemical character; enough contrast generally exists for chemical analyses of ground water to be an aid in geologic mapping where outcrops are scarce. In their chemical character and that of the water derived from them, the rocks may conveniently be divided into two groups. The first includes granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs; these rocks approximate granite in composition. They are rich in silica, and poor in calcium and magnesium. The second group includes diorite, gabbro, hornblende gneiss, and andesite flows and tuffs; these rocks approximate diorite in composition. They are poorer in silica and richer in calcium, magnesium, and iron. The granite group yields a soft, slightly acidic water that is low in dissolved mineral constituents; in contrast, the diorite group yields a hard, slightly alkaline water that is high in dissolved material.

Springs yield water which, although similar to well water in other respects, contains only about one-third the concentration of dissolved solids; its concentration shows that, on the average, spring discharge represents relatively shallow, rapid circulation.

Table 1 shows some chemical analyses of ground water from the major chemical groups of rocks in the Piedmont province of North Carolina. Table 2 includes a summary and comparison of the median analyses for water from the granite and diorite groups. The relatively high content of dissolved mineral matter in the water from the diorite group may be readily seen. This holds true for all constituents except iron, fluoride, and perhaps nitrate. It can be deduced from this comparison that water from a well in the Piedmont area having a hardness greater than 50 parts per million, a bicarbonate content greater than 70 parts per million, a dissolved-solids content greater than 110 parts per million, and a pH higher than 7.0 probably has passed through rocks of the diorite group.

According to available data, this classification of water holds true for

Table 2.- Summary and comparison of water from granitic and dioritic rocks

Chemical constituents (in parts per million, except pH)

	Granite [1]				Diorite [2]				Granite and diorite [3]			
	Median	Mean	Range		Median	Mean	Range		Median	Mean	Range	
			Low	High			Low	High			Low	High
Silica (SiO_2)	30	28	9.9	39	32	34	7.1	60	30	30	18	45
Iron (Fe)	.2	1.2	.01	8.7	.2	.6	.0	5.7	.1	.9	.02	5.7
Calcium (Ca)	5	5	1.8	12	38	49	13	174	20	20	6.8	37
Magnesium (Mg)	2	2	.6	4.5	12	12	2.6	40	4	5	2.4	7.6
Sodium and potassium (Na+K)	7	7	1.3	14	11	14	3.3	35	9	10	6.4	18
Bicarbonate (HCO_3)	34	35	12	80	127	137	50	304	74	86	48	132
Sulfate (SO_4)	2	4	.1	23	17	44	.1	391	3	9	1.2	36
Chloride (Cl)	2	4	1.1	17	14	28	1.4	204	2	6	1.4	35
Fluoride (F)	.1	.1	.0	.9	.1	.2	.0	1.8	.1	.2	.0	1.5
Nitrate (NO_3)	.9	2.9	.0	14	1.3	4.3	.0	30	.5	1.5	.1	7.6
Dissolved solids	71	75	25	123	233	289	106	696	120	127	80	187
Hardness as $CaCO_3$	23	25	8	58	145	172	52	482	63	68	27	124
pH	6.5	-----	5.8	7	7.1	----	6.5	8.2	6.9	----	6.6	7.1

[1] Water from wells in the granite group of rocks. Represents 29 analyses from table 1.

[2] Water from wells in the diorite group of rocks. Represents 23 analyses from table 1.

[3] Water from wells that penetrated both granite and diorite or hornblende gneiss. Represents 10 analyses from table 1.

about 95 percent of all well water in the igneous and metamorphic rocks in the Piedmont of North Carolina. It probably applies equally well in Maryland, Virginia, South Carolina, Georgia, and Alabama, and in other areas where the rocks, topography, and climate are similar to those in the Piedmont of North Carolina. However, it would not be appropriate to attempt to correlate these waters with those from similar rocks in arid regions because of the greatly different climate and recharge conditions.

Topography is a factor in the correlation of ground water in crystalline rocks because it is one of the principal factors affecting the rate of circulation. Water in the crystalline rocks of the mountains of North Carolina circulates more rapidly than water in the Piedmont rocks of the same type and is consequently lower in dissolved solids. Water from springs, in both the Piedmont and mountain provinces, circulates more rapidly than water from wells.

Despite these differences in dissolved solids of water in the same type of rock, waters from the granitic rocks throughout North Carolina are chemically similar. Waters from the dioritic rocks also are chemically similar. Chemical analyses of water are commonly expressed in parts per million, as in Table 1. Although this method of expression shows the chemical composition of the water, it does not readily indicate its chemical character. The analyses may be converted from parts per million to equivalents per million to show the composition in terms of chemically equivalent quantities, and then these quantities may be expressed in percentages. The similarity of water from springs and from wells in the Piedmont and mountain provinces that penetrate a given type of rock is made apparent by this method. Figure 1 shows, in percentages, the ionic composition in terms of equivalents per million of water

from individual springs in granite and diorite groups of rocks. The similarity of the water from wells in granite with that of spring water from granite is apparent. Also, the water from wells in diorite is similar to spring water from diorite. Bicarbonate is the predominant anion in water from both groups. However, the diorite water has calcium as the chief cation, whereas the granite water contains sodium and calcium in about equal proportions.

Even though Figure 1 compares the types of waters with respect to ionic composition, it does not give an accurate picture of the chemical character of the "granite" water because the high percentage of silica is not considered. The average silica content in both the granite and diorite waters is about 30 parts per million. However, the relatively low contents of other dissolved mineral constituents in water from granite results in the silica content being as much as 30 to 50 percent of the total dissolved solids. Some of the waters,

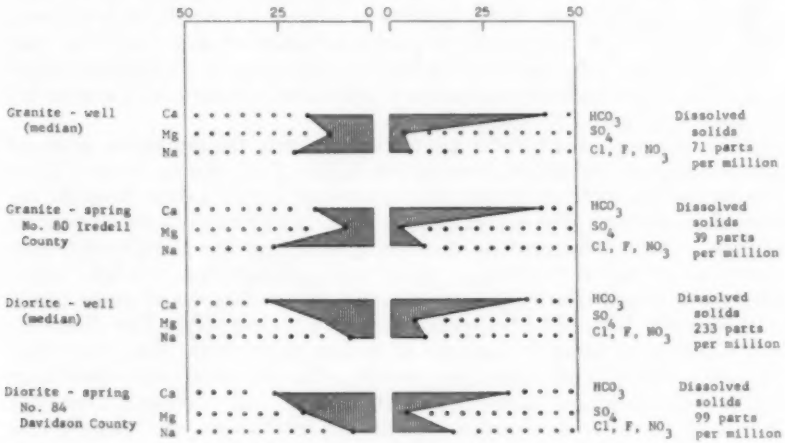

FIG. 1. Diagram showing, in percentage, the ionic composition in equivalents per million of water from wells and springs in granite and diorite.

therefore, could be referred to as "siliceous" instead of "calcium bicarbonate," "sodium calcium bicarbonate," or whatever else the ionic composition might seem to require.

ANOMALIES IN DISSOLVED SOLIDS

The majority of the waters analyzed from the Piedmont and mountain provinces of North Carolina may be classed as "granite water," "diorite water," or "intermediate water." Anomalies in dissolved mineral constituents may indicate either abnormal structural conditions resulting in abnormal rates of circulation or the presence of concentrated mineral deposits.

Structure.—Consideration should be given to what constitutes abnormal structural conditions and to how the chemical character of the water is affected by them. Such structures as close folding and small-scale faulting,

which are common, have not been shown to be responsible for unusual rates of water circulation in the consolidated rocks of North Carolina. In its path downward through the residual soil and decayed rock, as well as laterally through joints or other rock openings, during its movement toward a stream, the water is not affected chemically by the type of rock openings. Rather, it is affected by the chemical character of the rock and by the length of time it is in contact with the rock. Accordingly, only those structures that cause the circulation of water to be greatly accelerated or retarded might be detected by an appraisal of the chemical character of the water.

Circulation of water to great depths along a major fault plane and then upward to the surface along another plane seemingly is rare in the igneous and metamorphic rocks of the southern Appalachians. Although deep, slow, circulation would tend to increase the total mineral content of the water, high mineral content alone should not be taken as indicating a major fault. Deeply circulating water would be likely to have an abnormally high temperature. High temperature would be a safer indication of deep circulation than would the mineral content of the water, though water could circulate deeply without having a high temperature as it approached the surface, if it ascended no more rapidly than it descended.

The degree to which rocks are fractured affects the circulation of water and consequently affects its chemical character. This relation is not a direct one because the local topography has resulted, to a great extent, from the degree of fracturing. The topography, in turn, largely controls the circulation of water. Some homogeneous masses of granite have few joints except those caused by exfoliation (sheeting). Many such granite bodies form hills underlain by a thin layer of soil and decayed rock. Water does not penetrate deeply in these rocks but is shunted quickly toward a stream (2). The dissolved-solids content of water in this type of terrane is extremely low, lower than the average content of water from granite. On the other hand, some large bodies of poorly jointed gabbro occupy broad, flat areas, where only a few tens of feet of difference in elevation separate the interstream, or recharge, area from the stream area. In such areas, even though the circulation of water is very shallow, it is extremely slow because of the low gradient, and the water dissolves large quantities of minerals. Only in waters having unusually high or unusually low concentrations of dissolved solids is there a suggestion that the fracturing of the rock is abnormal. Even in these cases, the topography and depth of mantle rock may indicate the degree of fracturing better than does the water. In most cases, therefore, it is inadvisable to use the chemical character of water from igneous and metamorphic rocks as a basis for the interpretation of geologic structure.

Mineral Deposits.—Even though there is little evidence that chemical analyses of water have materially aided in the exploration of mineral deposits in the igneous and metamorphic rocks of the southern Appalachians, the potential use may be considerable. The prevalent contrast between the chemistry of a mineralized zone and that of the adjacent country rock may be reflected by corresponding contrasts in the chemical character of the water.

Much work needs to be done to determine the significance of this relationship in various types of mineral deposits.

The writer made a reconnaissance of the chemical character of the water in the gold belt at Gold Hill, Rowan County, N. C. Work by Laney (1) indi-

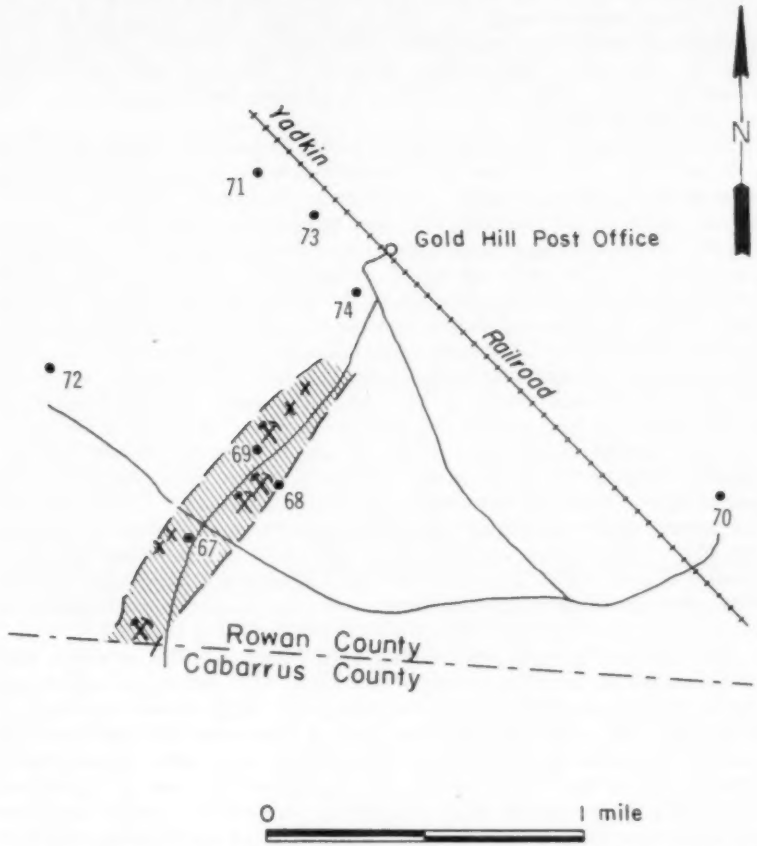

FIG. 2. Map of Gold Hill area, Rowan County, N. C., showing location of wells from which water analyses were made. Numbers correspond to serial numbers of analyses in Table 1. Sulfide ore zone (stippled pattern) is bounded on both sides by felsic schists and slates.

cated that the gold and copper occur with sulfide minerals as stringers in schist, and as veins in which quartz is the chief gangue mineral. The country rocks are highly siliceous schists, slates, and tuffs containing relatively insoluble minerals. Figure 2 is a map showing the sulfide zone and the location

of wells from which water samples were taken. Analyses of the samples are shown in Table 1. Water from the country rock contains much less dissolved solids than does the water in the sulfide zone. No explanation is readily apparent for the high chloride content of water from no. 69. The high sulfate content of water from nos. 67 and 68 is to be expected as a consequence of the infiltration of water through the zone of oxidation and into the sulfide zone. A sample of water from the Phoenix Gold mine in Cabarrus County, N. C. (no. 76), also has a high sulfate content. In this mine gold occurs with sulfides in quartz veins in association with scheelite, barite, and calcite. The country rock is andesite.

Where the water table is lowered in sulfide deposits by mining operations or by pumping wells, the zone of oxidation also is lowered to include the cone of depression in the water table. A change in the chemical character of water with a change in the pumping level may indicate the presence of a mineral deposit. An interesting example concerns a municipal well in Selma, Johnston County, N. C. The well was drilled in September 1953 to a depth of 300 feet; the only rock sample examined by the writer was at 200 feet and consisted of sericite schist and disseminated pyrite. Except for a relatively high iron content and low pH, the water originally appeared to be normal (no. 77a). The well was pumped continually until October 1954 with no noticeable change in the chemical quality of the water. The static water level was about 30 feet below the land surface, but during the period of pumping the water level was lowered to 150 feet. Then, for about 4 months the well was unpumped. During this period water replaced air in the rock fractures of the cone of depression as the water table rose to its natural level. When the well was pumped again on February 25, 1955, a sample was collected for analysis (no. 77b). The water was very acid (pH 2.5) and contained abnormal amounts of iron and sulfate. The change is attributed to oxidation of pyrite within the cone of depression while the well was pumped and to solution of the iron and sulfate as water filled the cone after pumping ceased.

The well was pumped continuously until March 8, 1955, at which time another sample of water was collected (no. 77c). The decrease in sulfate and iron in this sample indicates that less water was being drawn from storage around the well, where the previous cone of depression had developed the oxidized zone, and more water was being drawn from more remote places, where oxidation had not occurred. The extent of the cone of depression, representing the geometric solid occupied by the induced zone of oxidation after September 1953, is not known, but probably is not significantly more than 2,000 feet from the well in any direction. The writer can find only one logical explanation for the peculiar water—that it reflects a zone of sulfide minerals in the cone of depression that became partly oxidized when the water table was lowered by pumping.

Most of the igneous and metamorphic rocks contain more calcium than magnesium. This is reflected in most ground waters by a greater amount of calcium than magnesium in solution (Table 1). Conversely, magnesium-rich rocks yield more magnesium than calcium in solution. For example, water (no. 78) from an olivine deposit at Webster, Jackson County, N. C., contains more magnesium than calcium in solution.

CONCLUSION

Two normal types of ground water occur in the igneous and metamorphic rocks of the southern Appalachians. One type is characterized by low concentrations of dissolved solids, low hardness, pH less than 7, about equal amounts of sodium and calcium, and a considerable percentage of silica; this water is associated with felsic rocks such as granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs. The other type is characterized by a higher concentration of dissolved solids, greater hardness, pH greater than 7, a greater amount of calcium than sodium, and a content of silica that is comparable in amount but much lower in percentage than in the other water; this water is associated with mafic rocks such as diorite, gabbro, hornblende gneiss, and andesite flows and tuffs.

In many cases concentration of a chemical constituent in the rock leads to a concentration of that constituent or of an associated constituent in the dissolved solids in the water in the rock. Thus, water analyses offer a valuable geochemical tool to mineral prospecting in igneous and metamorphic terranes where a humid climate prevails. Laboratory facilities are necessary for a relatively complete and accurate water analysis. However, field kits for making tests of the chief dissolved constituents often offer the geologist a simple and quick method of determining the character of the ground water and of inferring the character of the host rock.

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RALEIGH, NORTH CAROLINA.
Aug. 8, 1957

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THE USE OF LEACHABLE URANIUM IN GEOCHEMICAL PROSPECTING ON THE COLORADO PLATEAU

II. THE DISTRIBUTION OF LEACHABLE URANIUM IN SURFACE SAMPLES IN THE VICINITY OF ORE BODIES

HEINRICH D. HOLLAND, GEORGE G. WITTER, JR., WILLIAM B. HEAD, III, AND RUTH W. PETTI

ABSTRACT

Determinations were made of the leachable uranium content of soil and rock samples from the vicinity of the Standard-Lisbon-Cal Uranium ore body, Big Indian Wash, Utah, the new Monument No. 1 ore body, Oljetoh, Arizona, a Shinarump and a Chinle deposit near Cameron, Arizona, and the Freedom No. 1 and No. 2 ore bodies near Marysvale, Utah. In the sedimentary uranium deposits studied the presence of uranium mineralization can be detected at considerable horizontal distances from ore, but surface samples at vertical distances of more than about 30 feet from ore gave no indication of the presence of ore at depth.

At Marysvale uranium was found to penetrate no farther than alteration visible in hand-specimen into the quartz monzonite wall rock of a uraninite-fluorite vein. Analyses of surface samples indicate that mineralization at the base of late Tertiary rhyolite can be detected at the surface through a fair thickness of rhyolite.

The data as a whole suggest that in areas in which uranium ore is present at shallow depths leachable uranium analyses can serve as a useful tool in exploration.

INTRODUCTION

PART I of this pair of papers on the use of leachable uranium in geochemical prospecting on the Colorado Plateau contained a description of the techniques used in measuring the concentration of total and leachable uranium, the alpha and beta-gamma activity of soil and rock samples, and a discussion of results obtained on core samples taken in the vicinity of the Homestake ore body, Big Indian Wash, San Juan County, Utah. Part II is concerned with the distribution of leachable uranium in surface samples near a number of mineralized areas and ore bodies on and adjacent to the Colorado Plateau. Since the analytical techniques used in determining the leachable uranium content of these samples are essentially the same as those described in Part I, they will not be described here, and the results obtained in each of the areas studied will be presented directly.

THE BIG INDIAN WASH AREA, SAN JUAN COUNTY, UTAH

The general geology of this area was described briefly in Part I. The surface samples were taken on the Chinle bench and on the cliff forming the

eastern edge of the bench. Figure 1 shows the geology of the area as well as the location of a number of drill holes and the approximate outline of a part of the Standard-Lisbon-Cal Uranium ore body. Soil covers most of the bench although a few resistant upper Chinle beds crop out near its eastern edge. On the cliff to the east of the bench beds of the lower Chinle and Upper Cutler formations are exposed.

On the Chinle bench samples were initially taken on a 100 foot grid, one edge of which was roughly parallel to the edge of the Chinle-Cutler cliff. Later additional samples were taken at intermediate points, and along a line

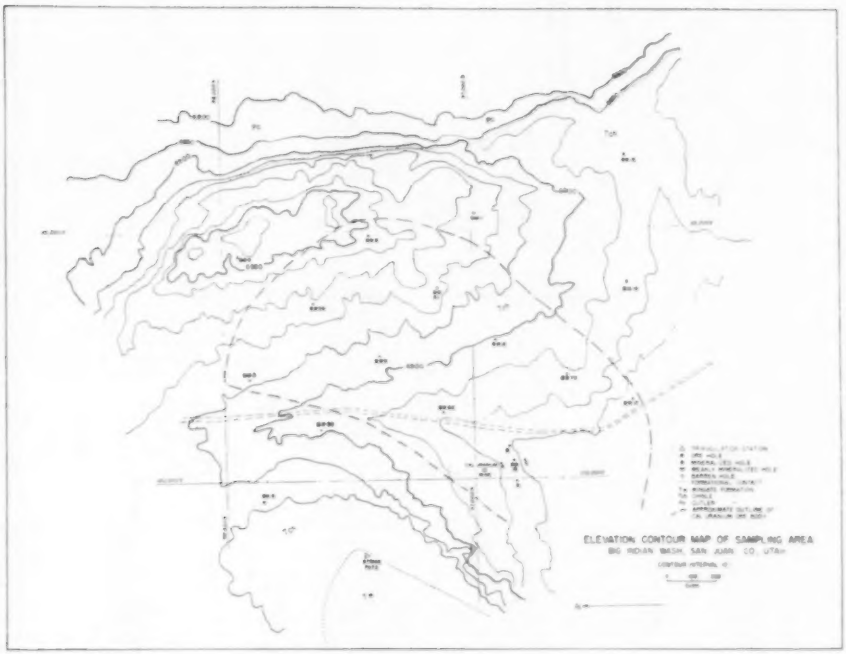


FIG. 1.

designed to cross the ore body. At each sample station soil from a depth of 2 inches was taken, and several samples at circa 6 and 10 inch depths were also collected. The soil was scooped into steel containers which were sealed with drafting tape to prevent contamination during transport. The data on the leachable uranium (LU) content of these samples are shown in Figures 2 and 3.

The lithology of the lower Chinle beds exposed on the Chinle-Cutler cliff is variable both laterally and vertically as can be seen from the data of Figure 4. Siltstones, fine, medium, and coarse sandstones, and conglomerates are

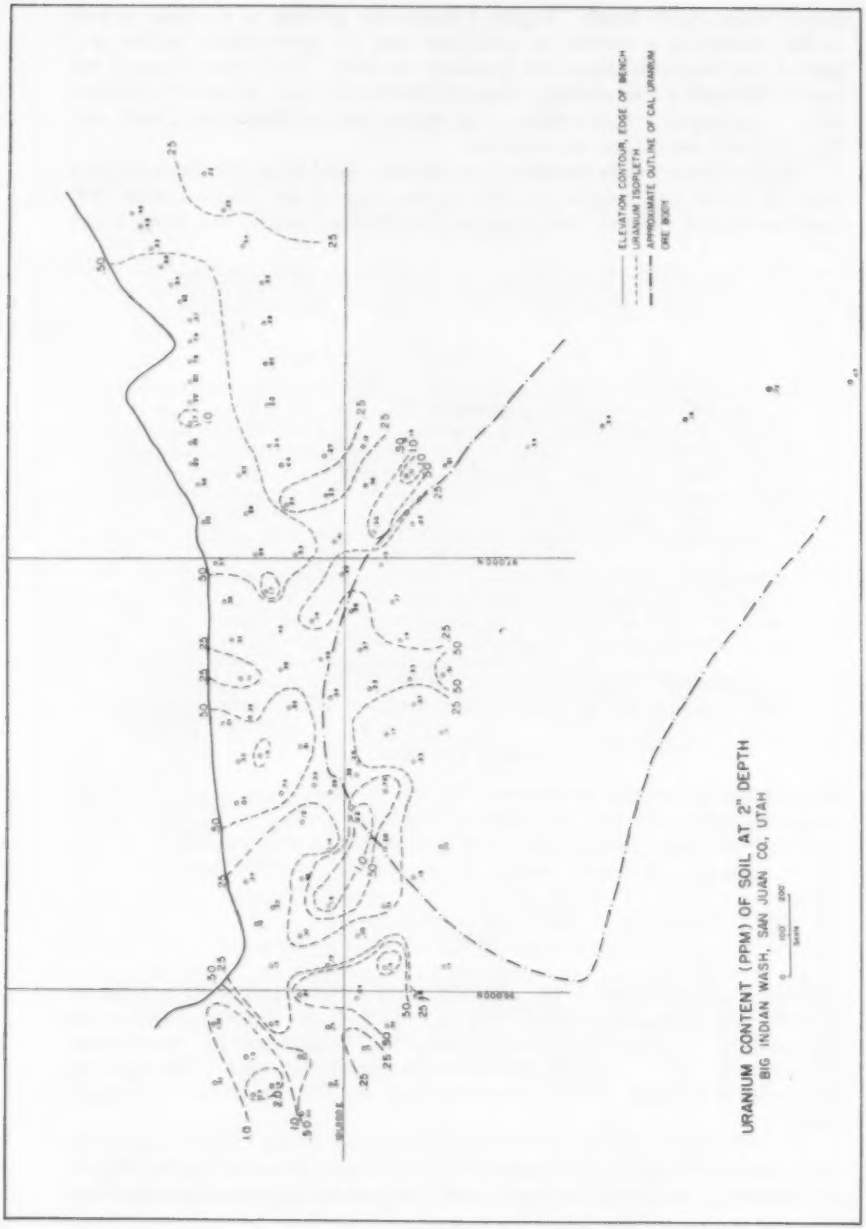

ELEVATION CONTOUR, EDGE OF BENCH
URANIUM ISOPLETH
APPROXIMATE OUTLINE OF CAL URANIUM ORE BODY
URANIUM CONTENT (PPM) OF SOIL AT 2" DEPTH
BIG INDIAN WASH, SAN JUAN CO., UTAH

FIG. 2.

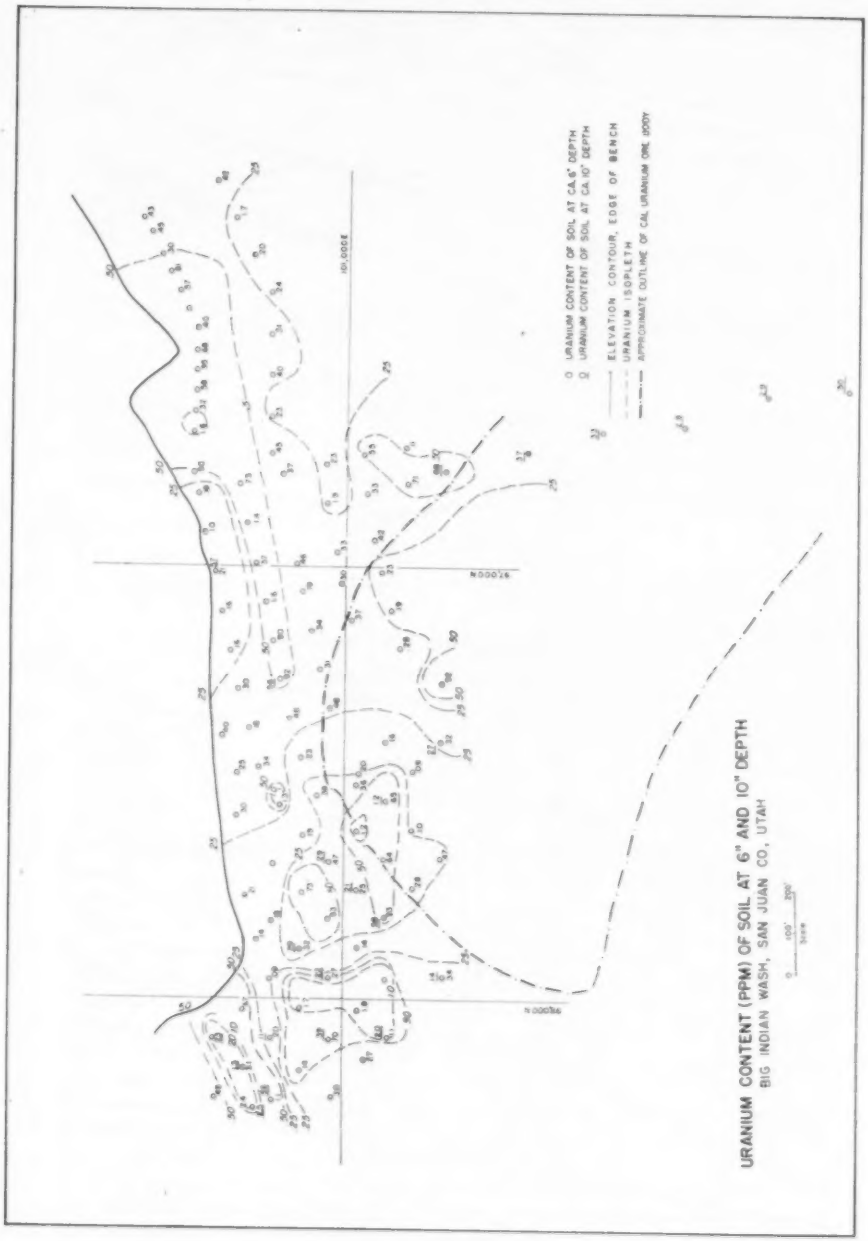

URANIUM CONTENT (PPM) OF SOIL AT 6" AND 10" DEPTH
BIG INDIAN WASH, SAN JUAN CO., UTAH
URANIUM CONTENT OF SOIL AT CA. 6" DEPTH
URANIUM CONTENT OF SOIL AT CA. 10" DEPTH
ELEVATION CONTOUR, EDGE OF BENCH
URANIUM ISOPLETH
APPROXIMATE OUTLINE OF CAL URANIUM ORE BODY

FIG. 3.

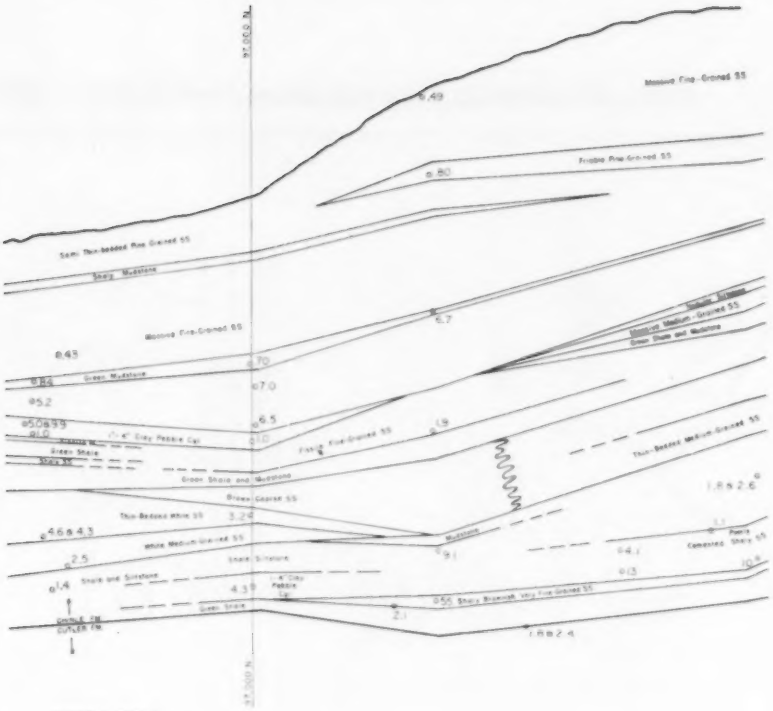


FIGURE 4, PART 1

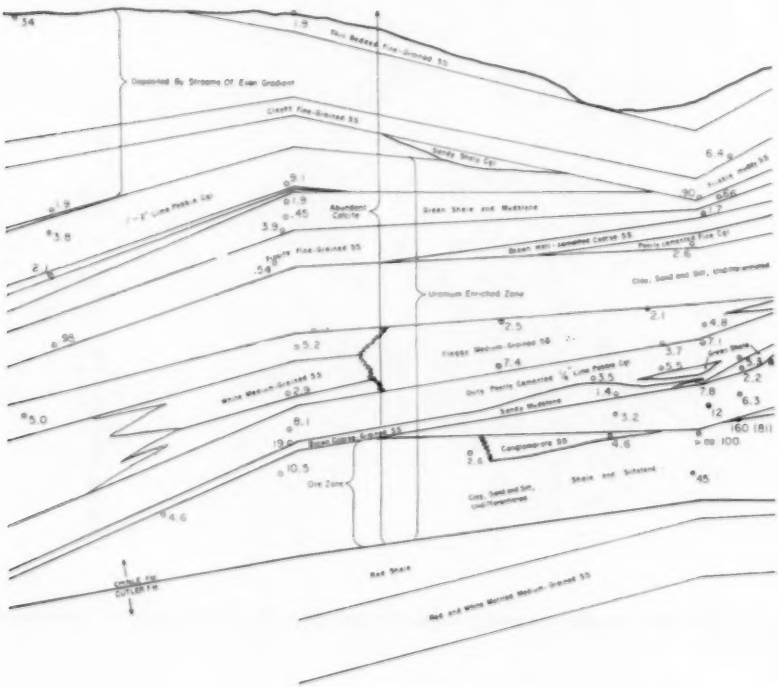


FIGURE 4, PART 2

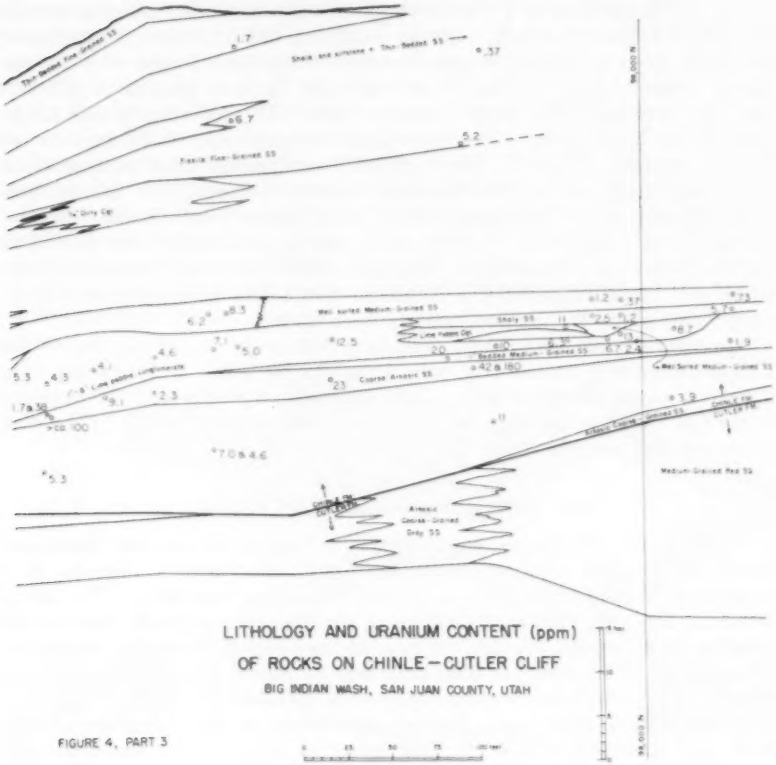


FIG. 4.

present and grade into each other rapidly in the cliff face. This type of lithology is apparently characteristic of lower Chinle sediments in the Big Indian Wash area. Fresh rock chips were collected from appreciably different rock units and were packed and sealed in the same manner as the soil samples. The data obtained on the cliff samples were shown in Figure 4.

From the data in Figures 2 and 3 it follows that the outline of the Cal-Uranium ore body is not reflected in the LU content of the soil samples. In this area the depth to ore varies from 80 to 200 feet from east to west In similar areas LU anomalies in soils can, therefore, not be expected to show through such a thickness of rock. The highest LU values were found in the NE corner of the sampling area. This area lies directly above the mineralized ground of the Small Fry claims, which is exposed on the Chinle-Cutler cliff. The variations in the LU concentration of soils in this area are probably related in a complex manner to the uranium content of exposed upper Chinle beds, the effects of vegetation, and a combination of mechanical transport and solution phenomena operating on the soil and exposed rock units of the area.

A very large range of LU concentrations was observed in the rock samples from the Chinle-Cutler cliff. In one small area the LU content approached ore grade while in others LU concentrations of less than 1 ppm were encountered. These differences were found not only between samples of different lithology but also within single lithologic units. This situation is thus analogous to that found in the core samples from the vicinity of the Homestake ore body as reported in Part I. The high LU concentration found particularly in coarse sandstone and in conglomeratic horizons indicates that the uranium mineralization of the Standard-Lisbon-Cal Uranium mine extends eastward to the Chinle-Cutler cliff. Such a conclusion is in harmony with that of an east-west trend of mineralization reported in Part I, which includes the Homestake and Standard-Lisbon-Cal Uranium mines and intersects the Chinle-Cutler cliff where the outcrop samples were taken.

Samples of the fine-grained sandstone that crops out at the top of the Chinle-Cutler cliff consistently were found to have low LU contents even directly above mineralized beds. It is thus not surprising that the presence of the Cal Uranium ore body was not found to be reflected in the LU content of surface soil samples.

THE MONUMENT VALLEY AREA, ARIZONA

Surface and cliff samples were taken in the vicinity of the new Monument No. 1 mine, which is located between Oljetoh and Kayenta, Arizona, in a small mesa capped by sandstones of the Shinarump formation. The ore is located in flat-lying Shinarump sediments filling an approximately north-south trending paleo-stream channel cut into the underlying Moenkopi formation. The geology of the area has been described by Baker (1) and Witkind and Thaden (7). The lower Triassic Moenkopi, 130–340 feet thick in this area, consists chiefly of thin, evenly bedded, dark brown to chocolate brown sandy shale and sandstone with a few thin lenses of light colored sandstone and purplish nodular limestone. Ripple marks, mudcracks, and raindrop impressions are common throughout the formation. An erosional surface here forms the top of the Moenkopi. A zone of bleaching at the contact between the Moenkopi and the overlying Shinarump formation is common and may be related to the deposition of ore in the basal Shinarump.

The Upper Triassic Shinarump, 0 to 210 feet thick in Monument Valley, is composed of sandstone with interbedded lenses of grit, conglomerate, and sandy mudstone (5). Shinarump sediments in paleo-stream channels tend to be conglomeratic and commonly contain slabs or pebbles of fine-grained materials, probably derived in part from the Moenkopi formation. At the top of the formation there is normally a zone of thin-bedded, medium to fine grained, yellowish brown sandstone, which grades into the overlying Chinle formation. Silicified and unsilicified logs, branches, and other carbonaceous material are characteristic of the Shinarump.

The mesa that contains the old and new Monument No. 1 ore bodies is approximately 600 yards long and 100 yards wide. The surface of the mesa is inclined slightly to the northwest and is quite irregular in detail. The

Shinarump has weathered into small, round knobs and domes that are commonly cut by nearly vertical joints. Two sets of these, one trending approximately N-S, the other approximately E-W, are quite prominent; at the southern end of the mesa the E-W set are particularly pronounced and are generally open, the distance between adjacent blocks commonly being as much as 2 or 3 feet. The Shinarump that caps the mesa is composed chiefly of a light buff-colored sandstone with a few stringers of conglomeratic material that are particularly common on the west side of the mesa. The sandstone is composed almost exclusively of medium sized, well sorted, well rounded quartz grains cemented by silica. Most of the larger fragments of the surface conglomerates are quartz pebbles. Indistinct bedding and cross bedding are visible on the outcrop, but in general the Shinarump exposed on the surface of the mesa is massive.

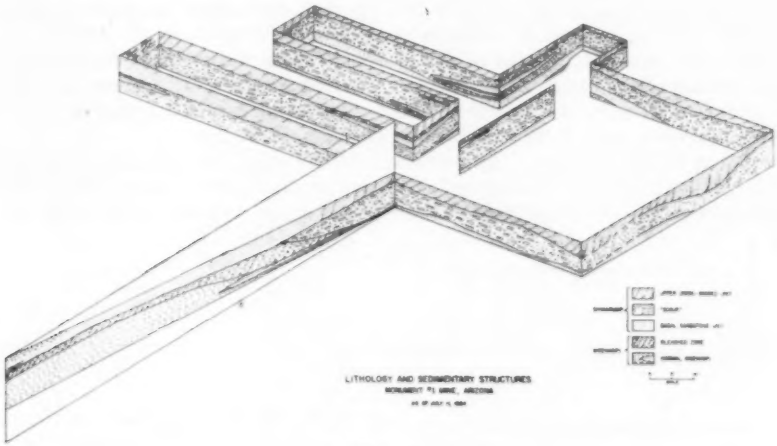


FIG. 5.

The Shinarump lithology within a portion of the mine is shown in Figure 5. Cross-bedded and non cross-bedded sandstones and the scour conglomerate are the predominant lithologies. The scour conglomerate is a mixture of mud flakes, pebbles of quartz and chert, and of sandstone size material. Finer clay materials usually surround the pebbles and flakes. Carbon trash is common, and branches and logs are numerous.

The ore is largely oxidized. Vanadium occurs in the ore minerals in valence states + 4 and + 5 and uranium in valence state + 6. The ore minerals shown in Table 1 were identified by means of X-ray powder patterns. The ore is mostly in the scour filling conglomerate and in the upper cross bedded sandstone unit shown in Figure 5. It is therefore essentially localized in the scour at the base of the paleo-stream channel. Introduction along the course of the channel and deposition in the reducing environment presented by the

TABLE 1

MINERALS OF THE NEW MONUMENT NO. 1 MINE, MONUMENT VALLEY, ARIZONA

Corvusite	Hewettite
Torbernite (or metazeunerite)	Jarosite
Carnotite	Malachite
Tyuyamunite	Gypsum
Volborthite	Quartz
Roscoelite type hydromica	

carbonaceous material of the scour fill is suggested as the most probable mode of origin of the ore body.

Samples for LU analysis were taken from the surface of the mesa and from the cliff that borders the mesa. The surface of the mesa is almost devoid of soil cover. Small channels were chiseled into the rock surface, and samples taken at the base of the channels at a depth of about 2 inches. The sampling interval was about 20 feet. Additional samples were taken at points of particular interest, such as at outcrops of peculiar lithologies, in the vicinity of joints, and near the remains of drill cuttings which were quite numerous on the surface of the mesa. The cliff was sampled systematically, along vertical sections on all sides of the mesa. These covered the exposed Shinarump and the uppermost part of the underlying Moenkopi formation.

Most of the analytical data obtained on the mesa surface are shown in Figure 6. This can be considered as an overlay on Figure 7, which shows the contours of a part of the base of the channel in the vicinity of the scour in

FIG. 6.

which the ore is largely located. The ore is not outlined with any degree of precision by the LU content of the suface samples. However, a number of anomalies are present on the mesa surface, which suggest the presence of ore at depth. The background LU content in this area seems to be less than 1 ppm as indicated by the LU content of the samples at the southern end of the sampling area. A detailed study near joints showed that the LU content of such samples is not significantly different from samples at some distance from joints. Similarly no correlation was obtained between coarseness or color and LU content of surface sandstone samples. Samples taken near drill cuttings from a mineralized hole did not show anomalously high LU values, suggesting that the observed anomalies were not controlled by the presence of such cuttings on the mesa surface. It follows that the anomalies shown in Figure 6 appear to be related to the presence of ore at depth. Whether the uranium now found in the surface was carried up from the ore horizon by ground water rising via capillary action and evaporating at the

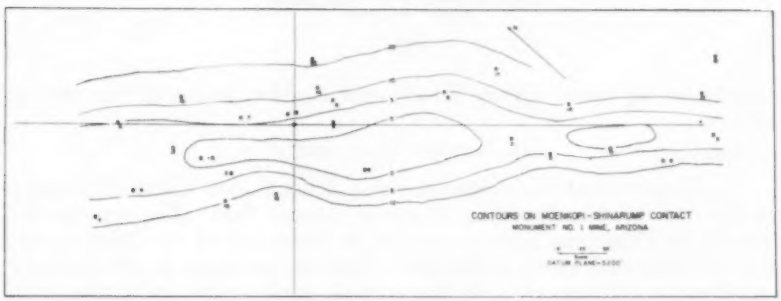
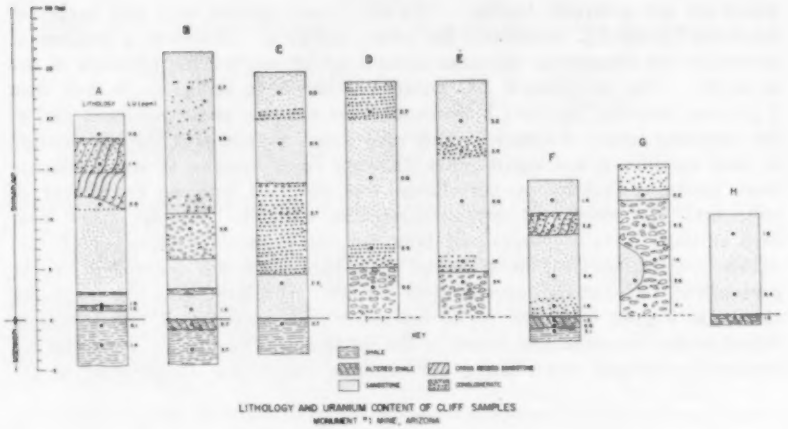


FIG. 7.

surface, or whether the uranium now present in the surface samples reflects a distribution produced at the time of ore deposition is difficult to determine.

All of the cliff samples except those taken near the Shinarump-Moenkopi contact were found to have low LU contents and to show no well-defined upward decrease except in the vicinity of the contact; these results suggest that anomalies are not supported by a LU gradient below the surface. The lithology and LU content of several cliff sections are shown in Figure 8. Almost all of the samples taken near the Shinarump-Moenkopi contact were found to possess anomalously high LU contents, which in many cases exceeded the highest values found at the surface of the mesa even though the lateral distance of the cliff samples to ore was several times the vertical distance to ore from the surface of the mesa. This indicates that the analysis of contact samples either from outcrops as in the present case or from drill core may serve as a useful guide to ore. In the similar situation encountered in the drill core materials from the vicinity of the Homestake ore body the same relationships were found (Part I). These are compatible with the concept that the solutions from which the ore minerals were deposited migrated predominantly



LITHOLOGY AND URANIUM CONTENT OF CLIFF SAMPLES
MONUMENT #1 MINE, ARIZONA

FIG. 8.

laterally leaving traces of their passage over a wider horizontal than vertical distance.

THE CAMERON AREA, ARIZONA

The Cameron area lies to the southeast of the Kaibab Uplift and slightly northeast of the San Francisco Mountain volcanic field. The ore deposits occur in the Shinarump formation and in the lower part of the Chinle formation, which here dip gently to the east. Deposits discovered to date lie along a north-south trending belt coinciding with the surface exposure of these rock units. In 1954 little exploration had been carried out to the east of the Little Colorado River where the favorable horizons disappear under middle and upper Chinle beds.

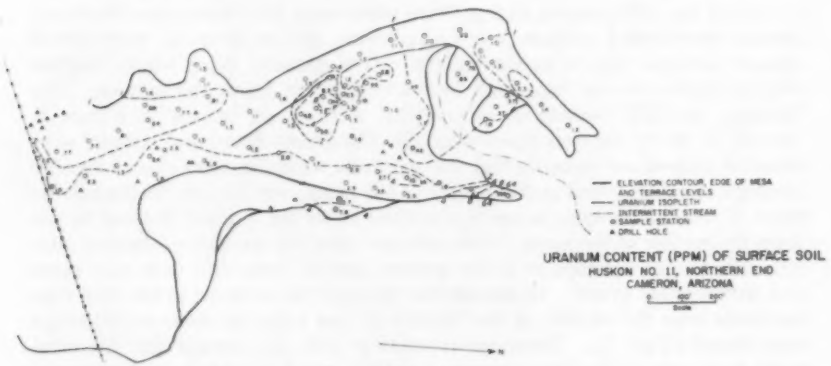


FIG. 9.

At least some of the Shinarump ore occurs in paleo-stream channels. The Chinle ore occurs in sandy portions of mounds that commonly rest as erosion remnants on an otherwise flat plain. It is not yet clear whether the Chinle ore occurs in lenses, or whether the lenses now exposed were joined at some time in the past to form paleo-stream channels. This question may be answered by further exploration on the east side of the Little Colorado River.

The principal ore minerals of the area are metatorbernite, metaautunite, and uraninite with minor amounts of uranophore, sabugalite, meta-zeunerite and zippeite (5, 3). Carbonaceous material is common in the Chinle deposits and may have contributed toward localizing the ore.

Analyses were carried out on samples from the vicinity of a Shinarump and a Chinle deposit.

The Shinarump Deposit.—Ore has been found in a paleo-stream channel filled with Shinarump sandstones and mudstones trending approximately north-

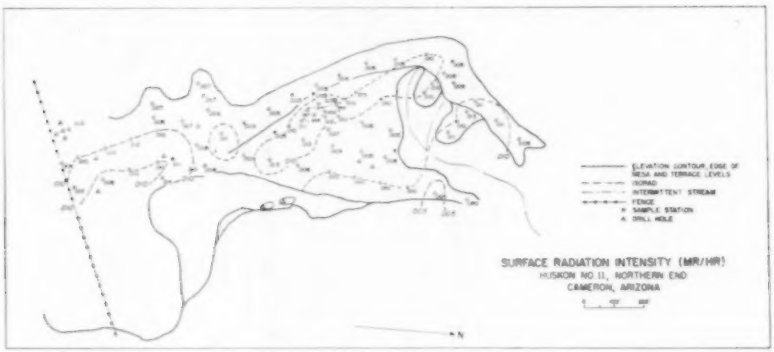


FIG. 10.

south and exposed near the west bank of the Little Colorado River south of Cameron. The deposit, Huskon No. 11, is in some sections contained in an erosional remnant exposed as a long ridge. The top of the ridge is generally flat, the edges gently sloping to vertical. Samples were taken from two sections of the channel called Huskon No. 11 North End and Huskon No. 11 South End respectively. The areas samples are shown in Figures 9, 10 and 11, as are the analytical data and radiation intensities obtained for samples taken and stations occupied in these areas.

LU anomalies and radiometric highs coincide satisfactorily, and the height of the LU anomalies is considerably greater than that of the radiometric anomalies, as might be expected on the basis of previous experience with the Homestake core samples (4). Drill hole information was available for three holes in the southern part of the area. The data for these holes are shown in Figure 12. It can be seen that LU anomalies are present over ore holes and that the intensity of the anomalies is directly proportional to the quantity of ore and

ELEVATION CONTOUR, EDGE OF RIDGE
SAMPLE LOCALITY
SAMPLE STATION
DRILL HOLE
URANIUM CONTENT (PPM) OF SURFACE SOILS
HUSKON NO 11, SOUTHERN END
CAMERON, ARIZONA
N

FIG. 11.

SURFACE RADIATION INTENSITY (MR/HR)
HUSKON NO. 11, SOUTHERN END
CAMERON, ARIZONA
ELEVATION CONTOUR, EDGE OF RIDGE
ISORAD
SAMPLE STATION
DRILL HOLE

FIG. 12.

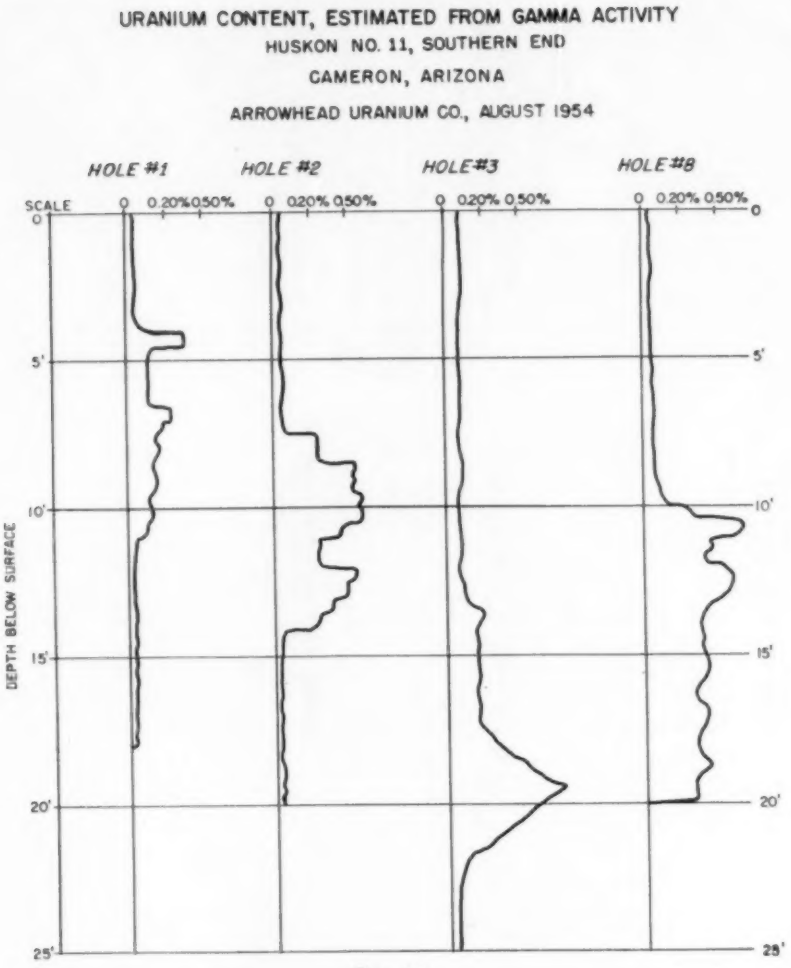


FIG. 13.

inversely proportional to the depth to ore. These relationships apparently hold in other parts of Huskon No. 11 as well.

The Chinle Deposit.—Chinle deposit Huskon No. 14, which lies at the eastern end of a flat plain south of Cameron, was sampled. It is bordered on the north, east and south by fairly steep slopes. The central part of the body has been eroded by what appears to be an intermittent creek, giving the deposit a crescent-like outline as shown in Figure 13. Bulldozer cuts have exposed an

ore horizon along the edge of the deposits 5 to 15 feet below the top of the mound.

Samples were collected on the top, the central depression and the area surrounding Huskon No. 14 as shown in Figures 13, 14 and 15. Surface samples were supplemented at approximately every fourth sample station by samples from 6 and 10 inch depths. All of the material consisted of soil mixed with pebbles up to several inches in diameter. In the laboratory only the fine-grained material was taken for analysis; the upper limit of grain size for the analyzed material was not well defined.

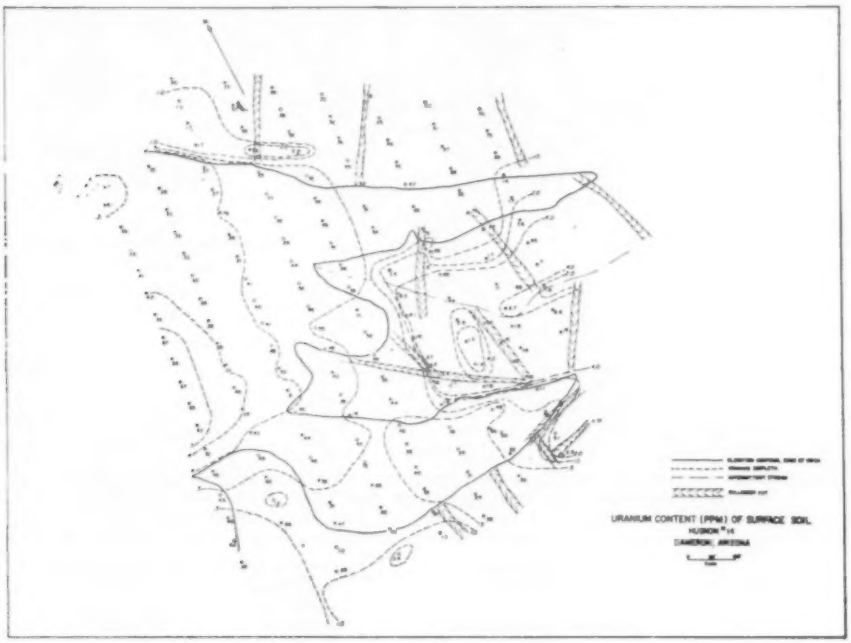


FIG. 14.

The position of the isorads and LU isopleths was found to coincide both for the surface samples and for those taken at depth. The relative difference in LU content between soil above mineralized and unmineralized ground is again somewhat greater than the corresponding difference in radiation intensity.

In the sequence of localities Big Indian Wash–Monument Valley–Cameron we have discussed the relationship of LU content and ore for samples that have been progressively closer to ore. In this sequence the correspondence between the LU content of surface samples and the presence of ore underground became correspondingly more pronounced. The impression obtained from this sequence is that serviceable correlations between LU analysis and

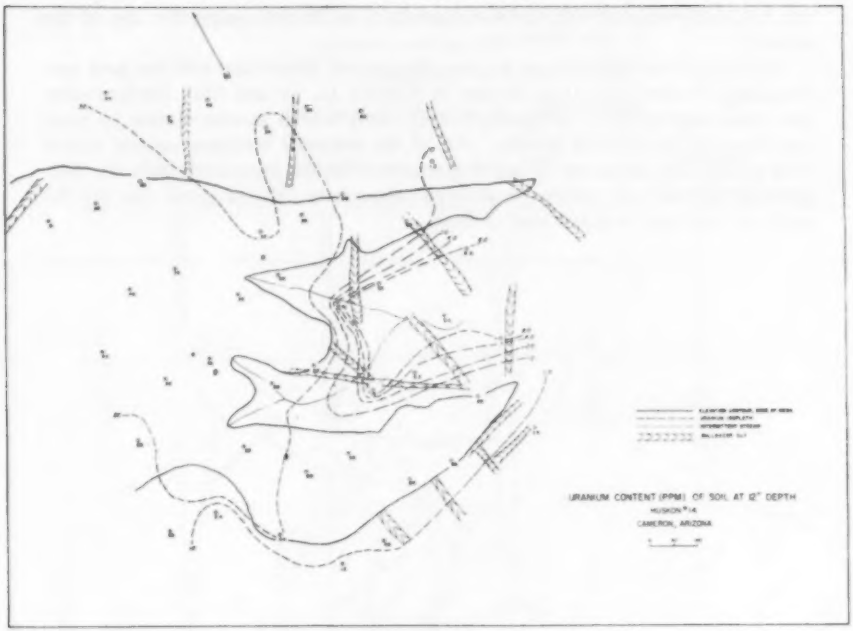


FIG. 15.

TABLE 2

SUMMARY OF DATA ON THE LOCATION, LITHOLOGY, AND LU CONTENT OF UNDERGROUND SAMPLES TAKEN NEAR THE INTERSECTION OF THE V.C.A. SHAFT AND THE DRIFT ALONG THE FREEDOM NO. 1 VEIN ON THE 300 FOOT LEVEL, MARYSVALE, UTAH

Sample no.	Hand specimen Lithology	Approximate distance to Freedom No. 1 vein (feet)	Leachable uranium (ppm)
30	yellowish brown altered quartz monzonite	0.5	1550
32	altered quartz monzonite	0.5	29
31	unaltered quartz monzonite	0.5	9.3
1	unaltered quartz monzonite	1.5	12
2	unaltered quartz monzonite	2	6.4
3	unaltered quartz monzonite	2.5	7.0
4	unaltered quartz monzonite	4	5.6
5	unaltered quartz monzonite	5	5.6
6	unaltered quartz monzonite	5.5	4.6
7	unaltered quartz monzonite	5.5	6.3
8	unaltered quartz monzonite	7	9.6
9	unaltered quartz monzonite	8	5.3
10	unaltered quartz monzonite	9	5.0
11	unaltered quartz monzonite	10.5	5.8
12	unaltered quartz monzonite	11	5.0
16	unaltered quartz monzonite	12.5	6.9

ore can be obtained when the depth to ore of the samples analyzed is less than ca. 20 feet at Cameron; there follows a "twilight" zone represented by the Monument Valley samples in which a vague correlation is observed, and beyond ca. 30 feet no serviceable correlation is to be expected, at least in the type of sedimentary sequence, structure and climate represented by the area studied.

FIG. 16.

THE MARYSVALE AREA, UTAH

Uraninite-fluorite veins in fault and joint planes cutting Tertiary quartz monzonite, and oxidized uranium minerals in near-surface deposits are found near Marysvale, Utah. The deposits have been described by Gruner, Fetzer and Rapaport (2) and, more recently, by Walker and Osterwald (6).

Both underground and surface samples were collected. The former were taken at the intersection of the cross-cut to the V.C.A. shaft and the drift on the 300 foot level along the Freedom No. 1 vein. The purpose of these samples was to study the penetration of uranium into the quartz monzonite wall rock of the uraninite-fluorite veins. Such data were expected to show whether LU analyses of core materials from such a geologic setting could serve as an aid in exploration. The results are shown in Table 2 and indicate strongly

that uranium did not penetrate into the wall rock further than rock alteration detectable in hand specimen. Thus, since uranium haloes do not surround the veins to any considerable extent, LU analyses of core materials are probably of no particular interest for purposes of exploration. However the data are of some interest from a structural point of view since they serve to emphasize the extreme importance of pre-existing planes of weakness in localizing the movement of uranium bearing solutions.

Surface samples were taken on "Rhyolite Ridge," the hill north of the Freedom No. 1 mine. The hill is underlain by quartz monzonite and is capped by late Tertiary rhyolite that flowed out on a quartz monzonite erosion surface. At least one uraninite-fluorite vein, the Freedom No. 2, rises through the quartz monzonite under the hill. The uranium mineralization is post-rhyolite, but the uraninite-fluorite veins do not continue into the rhyolite. Rather, mineralization seems to cease near the quartz monzonite-rhyolite con-

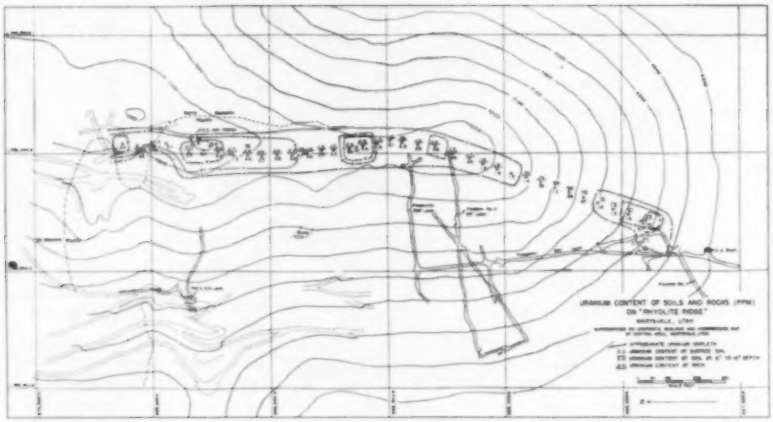


FIG. 17.

tact and strong alteration of the rhyolite at the surface is the only indication of this uranium mineralization. Samples of soil and rock were taken along the crest of the ridge to determine whether these would reflect the mineralization at the base of the rhyolite. The data obtained are shown in Figure 16. An anomaly was found where the Freedom No. 2 vein presumably intersects the rhyolite. Other anomalies were located as well, but their interpretation is uncertain at this time since adequate control at depth is not available. The data are reasonably encouraging and suggest that LU analyses may be of help in exploration in analogous geologic situations.

ACKNOWLEDGMENTS

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PRINCETON UNIVERSITY,
PRINCETON, N. J.
Oct. 22, 1957

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GALENA IN PYROMETASOMATIC DEPOSITS

PER GEIJER

ABSTRACT

Galena is uncommon in pyrometasomatic deposits but does occur in Precambrian sulfide deposits of this type in Central Sweden, in what were almost pure carbonate rocks. Associated minerals are in one deposit andradite and fluorite, but mostly magnesium-fluosilicates with tremolite or actinolite. Two contrasting deposits are associated with the same granite body; one is dominantly galena and other quite minor sulfides, the other is dominantly copper sulfides and galena is essentially absent. Thus, strong fractionation of sulfides must have occurred.

It is well known that galena is comparatively rare in high-temperature replacement deposits that are classed as pyrometasomatic or contact-pneumatolytic.[1] Furthermore, where it occurs in essential amounts in such, it is generally referred, not to pyrometasomatic process proper—i.e., the initial stage when the substances introduced through replacement into the carbonate rock were carried as gaseous compounds—but, mainly at least, to a later, hydrothermal stage. This opinion is based on decisive observational data. It is of interest therefore to bring together facts from a metallogenetic province in which galena characteristically occurs in deposits of pyrometasomatic origin and as a product of the pneumatolytic stage. This is true of the group of sulfide deposits in the Early Precambrian of Central Sweden that were genetically connected with the intrusion of the first group of Svionian granites; the mines of Falun and Sala are representative of different aspects of this sulfide mineralization.[2] It may be pointed out that the sulfide deposits associated with the *later,* palingenetic Svionian granites (8), which are somewhat different, are not included in this discussion.

A general feature of interest for the following discussion is the fact that the carbonate rocks (limestone and dolomite) before pneumatolytic action were rather pure, therefore silicates formed by internal metamorphic crystallization are very subordinate.

The following forms of mineral parageneses in replacement deposits in carbonate rocks may be regarded as distinct indicators of pneumatolytic processes: 1) The combination hematite or andradite garnet with fluorite, 2) magnesium fluo-silicates of the humite group, 3) ludwigite and some other borates, and 4) marialitic scapolite. Of these, scapolite has never been found

[1] The term "pyrometasomatic" is used here simply for the reason that it is relatively short. It is not happily chosen since the prefix "pyro" indicates a closer connection with molten magma than is intended, just as "contact" is unsuitable when so many deposits—such as those treated in the following—are rather far removed from any igneous contact. The best term would be "pneumato-metasomatic," but the length alone is deterring.

[2] A survey of the geology of this province has been given (in Swedish) by Geijer and Magnusson (5); a brief summary in English is by Magnusson (8).

in the deposits now considered, and the borates are restricted to certain magnetite deposits (4) and rarely associated with a little sphalerite, but the two first mentioned forms are represented by typical cases. In thus restricting the discussion to deposits where these mineral associations are found, the writer is well aware that a number of other gangue minerals also commonly occur as products of pyrometasomatism. However, these minerals, especially the amphiboles, also occur in deposits that are classed as hypothermal, and therefore their presence gives no unequivocal evidence of pyrometasomatic deposition.

The combination of andradite with fluorite may be regarded as a typical product of pneumatolytical action on limestone. The exact way in which the introduced substances were carried can, of course, never be proved, but a probable way is indicated by the reaction: $2\ FeF_3 + 3\ SiF_4 + 12\ CaCO_3 = Ca_3Fe_2Si_3O_{12} + 9\ CaF_2 + 12\ CO_2$. Andradite is not a common skarn mineral in the sulfide ores of the region. The introduction of these ores took place in the presence of great quantities of magnesium, either because the replaced rock was a dolomite or that magnesium was added with the sulfides ("magnesia metasomatism"). The rarity of the magnesium-free paragenesis is therefore not surprising. However, there are a few occurrences known, and in two of them the andradite is admixed with fluorite in almost equal quantity and occurring in such even distribution and textural relations with the andradite that contemporaneous deposition is proved. These two examples are in the Norberg district (3) and are known as the Kallmora "silver" mine and the Stripåsen copper mine.

At the Kallmora silver mine—there are also iron mines at Kallmora—galena is by far the predominating sulfide. The mine has long been idle, after having produced lead to the amount of about 15,000 metric tons (from data in Tegengren, 10). From a study of the dumps and remaining ore, and the official mine map and old reports, the following description is compiled. The chief galena-bearing unit was a body of andradite and fluorite that largely replaced a bed of limestone. Further, in a quartz-banded iron ore bed alongside the limestone, galena occurs as impregnations and veinlets; fissure fillings also are found in the adjacent leptite. Rich ore concentrations are reported to have been encountered in the garnet-fluorite body. From them probably also came some samples that consist of galena with pyrite, chalcopyrite, arsenopyrite, and a little bornite. Much more material has been available for study from the leaner portions of this ore body. It contains somewhat more garnet than fluorite, the latter as equidimensional grains enclosed in the garnet. There is also a little actinolite, and patches of quartz. The disseminated galena occupies interstices between grains of andradite. A little pyrite and chalcopyrite also occur, but sphalerite is extremely rare. Molybdenite is wide-spread, but the total quantity is very small. The regular association of galena with the combination andradite-fluorite indicates a closely similar origin. This does not imply, however, that *all* the galena of the deposit must belong to this stage. The small veinlets in the iron ore carry galena along with magnetite, chalcopyrite, pyrite, quartz, and fluorite, and may have been deposited later from solutions, possibly as a result of rearrangement within the deposit.

The subordinate role of the sulfides other than galena in the andradite-fluorite paragenesis at Kallmora becomes still more striking if one considers also the Stripåsen mine. This small mine, long since idle, is situated about 4 km from Kallmora, in a similar stratigraphical situation and at approximately the same distance (350–400 m) from the contact of the same granite body. These two are the only mines in the district that have been worked exclusively for sulfides, although there are a few concentrations of copper ore, evidently later introductions, in some of the iron ore deposits. At Stripåsen there is no remnant of limestone but the chalcopyrite occurred (chiefly at least) in a body of andradite and fluorite just as the galena at Kallmora. Some pyrite is also observed. In the surrounding rocks, altered to a quartzite (sometimes with almandite garnet and anthophyllite), flakes of molybdenite are also noted, as well as orthite. Cronstedt (1) reports the occurrence of "some" galena at one place in the mine, but the scarcity of the lead sulfide in this deposit is illustrated by the fact that the present writer, during extensive search on the dumps and the small remaining surface exposures of the deposit, failed to find even a single grain of galena.

Kallmora and Stripåsen thus illustrate a remarkable fractionation of the sulfides whereas otherwise the paragenesis is identical—with one interesting exception. The reddish brown andradite of Kallmora carries 2.80 percent MnO (2), that of Stripåsen, dark brown, has only 0.47 percent (6). In view of the fact that manganiferous gangue minerals, in both high- and low-temperature deposits, are more commonly associated with the sulfides of lead and zinc than with those of copper and iron, this difference appears significant. It accentuates the fractionation of the ore-forming emanations. Also, as manganiferous silicates are of rare occurrence in pyrometasomatic deposits, it appears to connect the galena at Kallmora still more decidedly with the pneumatolytic phase.

Although andradite is a comparatively rare gangue mineral in the group of sulfide deposits in Central Sweden now considered, the magnesium fluo-silicates (humite group) are wide-spread and particularly common in connection with galena-sphalerite deposits. Chondrodite is by far the most important, but also clinohumite is present. The chondrodite does not, as a rule, form solid skarn masses but occurs preferably in the ophicalcite [3] pattern, as a sprinkling in a matrix of calcite. Since there is ample evidence that great quantities of magnesium have accompanied the sulfide mineralization of this metallogenetic epoch, one may regard all the components of the chondrodite as introduced together. However, in many cases it is clear that the replaced rock was a dolomite, and that the crystallization of the fluo-silicate consumed the magnesium of the carbonate, leaving behind a pure limestone. Obviously this fact does not exclude the possibility that magnesium also was introduced at this stage. The mode of occurrence of the chondrodite as just described lends support to the hypothesis that silicon was introduced as fluoride.

[3] As originally defined, the term ophicalcite should be reserved for such cases where the original mineral has been altered to serpentine. It seems practical, however, to use it for the characteristic appearance, also when the original product is preserved. It has long been employed in this sense, also by the present writer.

The relations of galena to chondrodite (and clinohumite) may be illustrated by a few examples.

In the small Koberg mine, not far from the iron mines of Persberg, the sulfides, including galena, accompanied by chondrodite and some other skarn minerals form vein-like dissemination streaks in the carbonate rock. The regular association links the deposition of the galena with that of the fluosilicate.

The geology of the Kaveltorp mines, now exhausted after having produced considerable amounts of lead, zinc, and copper ore, is well known thanks to Magnusson's studies (*7*). The stages in which replacement has advanced in the dolomite are registered in a zoning that is depicted as follows. The first zone shows the dolomite changed into ophicalcite with olivine or clinohumite, but further out instead with chondrodite. The following zones are actinolite and then tremolite skarn, the chondrodite persisting as a subordinate component. The tremolite skarn, again, gradually gives place to a skarn of anthophyllite and cummingtonite. Galena (like sphalerite) is chiefly associated with the tremolite and anthophyllite-cummingtonite skarns. It occurs in other skarn varieties also but is then, according to Magnusson, of later origin than the associated silicates.

In assigning the place of the galena in this replacement process—whether it belongs to a pyrometasomatic stage or to a later hydrothermal one—the following facts appear to the present writer to be important.

Mineral collections contain many specimens from Kaveltorp showing fine crystals of unaltered chondrodite in a matrix of galena. Whatever the length of the interval that may have elapsed between the formation of these two minerals, it is clear that the chondrodite has not been subjected to any hydrothermal action in connection with the emplacement of the galena. For such a process could hardly have failed to produce at least a partial serpentinization of the chondrodite. Nor is the development of anthophyllite, with which galena is preferably associated, reported to have been accompanied by any such changes. Alteration of the magnesian amphiboles to talc, as described by Magnusson, is a later process. Summarily, Magnusson remarks that the lead-zinc ores of the deposit carry a much greater amount of fluorine-bearing minerals (chondrodite, phlogopite, and fluorite) than those containing mainly copper and iron sulfides. This, according to the present writer's experience, appears to be a general rule in this metallogenetic province.

However, there is evidence, reported by Ödman (*9*) from a microscopic study of the ore minerals of Kaveltorp, that some re-deposition of galena has taken place there during the hydrothermal activity, which in the skarns caused the common serpentinization and the formation of talc; several other sulfides were formed in the same way. But the amount of galena of this origin is small, and the fact does not affect the general conclusion that the deposition of the lead sulfide essentially took place during the typically pheumatolytic stage. Also it must be noted that there is no indication that any galena *was brought into the deposit* during the hydrothermal stage.

Pyrometasomatic deposition of galena thus has been a common and even a characteristic feature of the earlier Svionian sulfide mineralization in Central

Sweden. The question then presents itself: Is it possible to point out any special conditions that can explain this exception from the general rule? All that can be said on this subject is that a possible cause may be indicated by the different geological setting. For most pyrometasomatic deposits the world over are associated with igneous bodies intruded at moderate depths and then surrounded by large volumes of much cooler rocks. In the case of the Swedish metallogenetic province now considered, intrusion presumably took place at great depths and certainly in a formation that was heated all through, with comparatively low-temperature gradients. The granites, with whose emplacement the sulfide invasion was more or less directly connected, at least equal in volume the intruded formation, and they were intruded when folding of the latter was already far advanced. Rarely is there any close geographical association of granite and sulfide deposit. But it must, for the present, be left an open question whether these conditions of temperature and pressure really were the deciding factor.

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DISCUSSIONS

THE PARAGENESIS OF ACCESSORY MINERALS IN IGNEOUS ROCKS

Sir: In an article by W. W. Moorhouse in this Journal (2) it is stated that the Rosenbusch Order of Crystallization in igneous rocks is "downright misleading," especially as regards the early separation of some minor constituents, and that it was "superseded long ago by Bowen's Reaction Series."

First, it should be pointed out that the Rosenbusch Order has on the contrary been confirmed by Bowen himself, who states, ". . . many (petrologists) went the length of doubting the truth of the 'normal' order; such exceptions as could be adduced were made much of, but the only result of this was to show plainly that the exceptions point the rule" (1, p. 109). Bowen also observed that this order is parallel to his Reaction Series which is no more than a somewhat modified statement of the normal order of crystallization (1, p. 110). Rosenbusch set up his order from the microscopical study of textural relationships in igneous rocks. Moorhouse cites from Shand the pitfalls to be avoided in the paragenetical interpretation of textures; his examples however are fallacious. For instance, it is stated, ". . . no one seriously suggests that grains of zoisite or sericite enclosed in plagioclase, or perthitic blebs of albite enveloped in microcline are therefore earlier than the enclosing crystals. We know (!) that the first are alteration products, that the second is an exsolution phenomenon; but is this a logical reason for applying a different rule to such cases, than we apply to enclosures of apatite or zircon in the major constituents of igneous rocks?" The comparison is incongruous. It is well known that the habit of apatite, zircon, and other primary accessories in igneous rocks is quite different (discrete, idiomorphic crystals) from the habit of zoisite and sericite replacing plagioclase or albite exsolved from potassic feldspar. "Again, it is a familiar observation to ore geologists that many minerals . . . have developed euhedral crystal form *by replacement* of a pre-existing rock. No one would claim that euhedral pyrite in a shale, euhedral albite in an adinole, or euhedral arsenopyrite in a greenstone schist, by virtue of their crystal form were therefore the oldest minerals in the paragenesis of the rock. They developed epigenetically, by replacing or pushing aside the original minerals. Yet in an igneous rock, the euhedral crystal is regarded as *prima facie* evidence of early crystallization. I can see no reason why one rule should apply, let us say to pyrite in a schist and another to pyrite in a granite, or why one rule should apply to tourmaline and another to apatite in the same igneous rock." These likewise are widely dissimilar things; the formation of pyrite cannot be equated with the crystallization of

apatite or zircon and the reasoning above would only hold if, for instance, zircon were known to occur as idioblasts in shales in the same way as pyrite. The primary textures of igneous rocks are in general markedly different from the secondary fabrics of crystalloblastic rocks. Lastly, "When a rock contains both large and small crystals, it is to be presumed that the large crystals started to grow first." No petrographer would seriously presume this *a priori* without qualification.

The Rosenbusch Rule, which is only a convenient generalization, has of course its exceptions, as Rosenbusch himself was aware of, and these also hold for the Reaction Series (to name one, a quartz bipyramid generation earlier than feldspar in certain granites). Moorhouse disagrees emphatically with the early crystallization of accessories, especially the minerals apatite, zircon and sphene, and affirms that they are ***not*** in general the first minerals to crystallize in igneous rocks. It may be stated that the accessory minerals in igneous rocks can, and should, be distinguished as primary (early) and secondary (late). Not making this distinction leads to unfortunate confusions. In most igneous rocks, for example, zircon, monazite, xenotime, apatite, magnetite and ilmenite, when present, occur as small idiomorphic crystals of, it is here contended, early formation. Texturally this is evidenced, among others, by their preferential distribution or concentration in the *earliest* main constituents, such as biotite and hornblende in granites or in the minerals replacing and pseudomorphosing these. Of this more below. Moorhouse states that this is in contradiction with the theoretical consideration that minor constituents in a magma should crystallize last. Many theoretical considerations about how magmas should behave have come and gone. Concerning the case of sphene, a mineral that is commonly demonstrably late in sequence in igneous rocks (textural evidence!), Moorhouse knows of no reason why zircon and more complex silicates should not behave in the same way. The reason is probably to be sought in the presence of water and/or fluorine in considerable amount in sphene, presumably substituting oxygen in its lattice (3). In their investigation of trace element distribution in the Skaergaard pluton, Wager and Mitchell (6) show that Zr, Y, La and others are concentrated in the residual liquid originated by fractionation of an initial basic magma, and thus become relatively abundant in the latest granite fraction, where zircon separates owing to "the extreme insolubility of zirconium in acid magmas." I know of no case of normal igneous rocks in which zircon is demonstrably late in crystallization; the few cases on record are from exceptional local rock types with, significantly, very high zirconia contents. Apatite, on the other hand, is well known as a late-stage mineral in certain rocks (e.g. greisens); the distinction between early and late apatite is easily made on the basis of different habit, size, textural behaviour, etc. The same holds for magnetite and ilmenite. It should not be inferred from the occurrence of late apatite or magnetite, e.g. in basic rocks, that these minerals are late in all igneous rocks.

Moorhouse confined his attention to zircon, apatite, sphene and magnetite, in the habit of primary accessories, and gives an interesting statistical treatment of their textural associations, from which a definite distributional pattern

emerges. What he calls their "erratic distribution" is in fact their preferential distribution in hornblende and biotite, long known to petrographers (it is mentioned, e.g., in the original description of the Triberg, Schwarzwald, granite (7) figured by Moorhouse). It is observed, "Even a cursory examination of thin sections indicates a marked preference of such minerals as apatite, sphene, and zircon for biotite, hornblende and magnetite. A very high proportion of the accessories is found either in contact with or within these minerals." However, magnetite should be grouped with apatite, etc., for it likewise is an accessory, occurring as inclusions in biotite and hornblende, whereas zircon and apatite are but uncommonly enclosed by magnetite or ilmenite.

As regards the association of apatite with biotite and hornblende, it is affirmed, "Since biotite and hornblende in basic rocks belong to the late magmatic or deuteric stages, apatite must crystallize in this stage rather than in the early magmatic stage of olivine, pyroxene and plagioclase." And, "To sum up, the apatite and magnetite of the basic rocks are associated particularly with hornblende, uralite, and biotite. These minerals belong to the late magmatic or deuteric stages of such rocks . . . and this evidence therefore constitutes convincing proof that the accessory minerals crystallized at a late stage in the cooling history of the rock." This statement ignores that biotite, hornblende and uralite in these rocks replace olivine and pyroxene, not plagioclase, so that the association holds with the early femics too: apatite has been inherited from them and is therefore not late. Similarly, quartz, although latest in sequence in igneous rocks in general, is among the most corrosive rock components, especially in granites, but does not replace zircon or apatite; it retains the idiomorphic crystals of these primary accessories from the main constituents it may have replaced. Every petrographer is familiar with the ragged edges of biotite or hornblende in process of replacement, from which the zircon or apatite crystals protrude into the replacing quartz. In granites, biotite is often replaced to much varying extents by chlorite; surely, when finding zircon crystals in a chlorite pseudomorph after biotite, no petrographer would suggest that zircon must be late and replacive because chlorite is so.

As a result of failing to take into account the reaction relationships between earlier and later femic minerals in basic rocks, Moorhouse is bewildered to find that the primary accessories still show a very strong preference for biotite and hornblende in intermediate and acid rocks too: "The case of the intermediate and acid rocks poses a question for in these rocks, as well as in the basic ones, one finds that the accessory minerals still show a preference for biotite and hornblende. Must we then conclude that in such rocks the apatite, magnetite, and sphene, crystallized along with these minerals as original precipitates of the magma? Or are biotite and hornblende of relatively late crystallization themselves?" The occurrence, for instance, of idiomorphic biotite plates enclosed in plagioclase or of biotite somewhat deformed owing to appression between growing plagioclase crystals in granites shows that the biotite is early, not late.

The strong preferential distribution of the primary accessories in early

main constituents, conspicuous even in cursory examination of rock slides and well substantiated by Moorhouse's statistics, is a phenomenon *confined to igneous rocks*, and this puzzles Moorhouse: "Indeed, one should expect a granite to resemble metamorphic rocks rather than igneous rocks, as far as the distribution of its accessory minerals is concerned. In the intermediate rocks such as granodiorites, quartz diorites and monzonites, it is reasonably certain that such recrystallization has not been all-pervasive, since primary features such as plagioclase zoning survive." In schists and gneisses of sedimentary origin the accessories in question are much more evenly distributed. If they crystallized late it is hard to see what could have caused this marked difference between granites and metagneisses.

I have elsewhere (4, 5) put forward an explanation for this feature. Zircon and the other primary accessories crystallize early and move about in the magma (they may serve as convenient crystallization centres for the older main constituents) and become successively incorporated in the early main constituents, such as biotite and hornblende in granites, by coming into contact with, and adhering to, growth surfaces of the latter. In order to effect the high concentrations of primary accessories in biotite, etc., seen in many igneous rocks, there must have been a certain amount of internal movement in the magmas so that most of the separated primary accessories came into contact with growing biotite, to be enclosed by it. This movement may be correlated with intrusion.

Therefore, the preferential distribution of primary accessories in early main constituents is a *criterion for magmatic crystallization*, and as such useful in the study of granites and gneisses where the distinction between igneous and non-igneous mode of origin is sometimes difficult to make. This was also found by Moorhouse: "That granites in this respect more closely resemble igneous rocks than gneisses suggests that they are produced by crystallization of magma rather than by metasomatism or other metamorphic processes."

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EMPRESA DO COBRE DE ANGOLA
MAVOIO, ANGOLA,
Dec. 16, 1957

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ORE GENESIS—THE SOURCE BED CONCEPT

Sir: The article by C. L. Knight (Econ. Geol., v. 52, no. 7, p. 808–817) illustrates the type of independently developed theory that enriches geology. I am sure that those better informed than I am on the specific districts named will rise to dispute certain of his points.

The fact that certain rock formations, generally sedimentary horizons, are the favored host rocks in mining districts has been known and successfully exploited for many years, particularly in bedded or manto type deposits. The facts seem to be that any horizon that best satisfied the chemical, physical and mechanical factors of ore deposition has been overwhelmingly favored in volume of ore deposition, yet I see no reason for concluding thereby that ore minerals were syngenetic and either consolidated as ore bodies or subjected to later lateral concentration.

The assumption that sulphide ore minerals may be concentrated by lateral migration again faces us with the problem of the nature of the solution that moves them.

In the case of the deposits at Bou Beker (example 6) the secondary dolomite commonly has chalcopyrite crystals perched on the dolomite crystals in the voids, so that the author would have to hypothecate (1) a solution to move the lead and zinc sulphides and reprecipitate them, (2) a solution to bring in the dolomite and (3) another solution to bring in the chalcopyrite from somewhere and reprecipitate it. Overlapping types of mineralization are well known in ore bodies that appear to be directly associated with intrusives.

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REVIEWS

The Diamonds of Siberia. By A. P. Bobrievich and others. Pp. 158; figs. 192, map 1. Gosudarstvennoe nauchnotekhnicheskoe izdatel'stvo literatury po geologii i okhrane nedr, Moscow 1957. Price, Roubles 14.85. (In Russian.)

This book is contributed by 14 authors and presents an account of preliminary studies, during the period of 1954–1956, of diamond deposits in the basin of Vilyuy, the left tributary of Lena River, in eastern Siberia. The diamond deposits occur in an area of 300,000 sq km in the central part of the Siberian platform. There are two subprovinces where the diamond-bearing kimberlite pipes have been discovered. Both subprovinces are located on the border of the Tungusian syneclise where the stratigraphic sequence is represented almost exclusively by Ordovician carbonaceous formations and trap effusives. The southern subprovince is located in the basin of Malaya Botuobiya River (tributary of Vilyuy), and is associated with a local swell on the slope of Mesozoic subsidence. The largest kimberlite pipe "Mir," measuring 490 by 320 m, was discovered in this region within Ordovician dolomites, limestones, and marls. The pipes are filled with brecciated kimberlite with inclusions of related ultrabasic rocks, eclogites, and Archean crystalline schists. The inclusions of limestone are not altered. Generally, kimberlite contains up to 50 percent of foreign material. Slickensides are developed on the surface of kimberlite fragments, especially near the contact with the country rock. The fractures served as channels for hydrothermal solutions that resulted in carbonatization of kimberlite. The southern subprovince is located in the basin of Daaldyn River, on the northeastern border of the syneclise. Here again, the veritical kimberlite pipes pierce horizontal carbonaceous deposits of Lower Paleozoic age, with trap intrusions forming dikes and sills. The swarms of kimberlite pipes are structurally related to deep tectonic fractures; however, the area of predominant distribution of kimberlite pipes is located outside the region of maximum development of trap. In this subprovince, the diameters of pipes range from 40 to 600 m (pipe "Zarnitsa"). The age of kimberlite pipes is considered as post-Permian, and even as post-Triassic.

The kimberlites are composed of olivine, phlogopite, augite, ilmenite, perovskite, and apatite. The diamonds are associated with this suite of minerals. Pyrope, monoclinic pyroxene, spinel, chromite, kyanite, corundum, and rutile are present as fragments derived from xenoliths. The secondary minerals are represented by serpentine, calcite, quartz, dolomite, chalcedony, and zeolites. The pyrope-rich xenoliths of eclogite represent a rock unknown within the Siberian Archean formations. The association of kimberlite with eclogites throughout the world demonstrates a close genetic relationship of these rocks. A gradual transition between Archean hypersthene schists and eclogite has been recorded in xenoliths in kimberlite. The most characteristic companions of diamond are pyrope and ilmenite. Pyrope from kimberlite has a higher content of chromium and calcium than pyrope from other rocks. Ilmenite, in turn, contains considerably more iron and magnesium oxide than the ordinary ilmenite. Chromium and vanadium are present in ilmenite taken from kimberlite, and are absent in ilmenite from trap.

The diamonds in primary deposits and in placers range in weight from 0.1 mg to several metric carats. The largest diamond found weighed 32.5 metric carats. The diamonds are represented by crystals of octahedral, dodecahedral, or transitional habitus. The majority of diamonds are colorless; some yellowish crystals are encountered. Graphite inclusions along fractures are epigenetic. Graphite is also present in diamonds in a disseminated state. Microscopic inclusions of olivine, pyrope, and chrome spinel within diamonds have been recorded.

The friable deposits of the Vilyuy River Basin contain diamonds almost everywhere. These sediments are pre-Quaternary and Quaternary in age. The most prolific placers contain, besides diamonds, pyrope, ilmenite, chrome diopside, and perovskite. These minerals serve as indicators of diamond. The decrease of average weight of diamonds downstream amounts to 3–4 mg per 100 km. Pyrope withstands transportation as far as 150–200 km from the source.

The exploration includes panning, with the purpose of studying the concentration of pyrope in placers, and to trace it back to the primary deposit. From placers with high concentration of pyrope, samples are taken for determination of diamond content. The magnetic survey, especially the airborne, has been successfully used for detection of kimberlite pipes.

The authors are cautious as to the problem of the genesis of the primary diamond deposits. They postulate that the basic reserves of diamonds in Vilyuy Basin are connected with the kimberlite, and to a minor degree with the placers. Geologic parallels between the Siberian and African deposits have been drawn in several cases.

The Siberian diamonds are relatively of a low quality due to their small size and fragmentation, especially in placers. Diamonds of gem quality are rare. The deposits are considered by the authors to be of the same magnitude as those of South Africa. It is suggested that they can entirely satisfy the demand for industrial diamonds in Soviet Union.

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Dec. 27, 1957

Principles of Engineering Geology and Geotechnics. By DIMITRI P. KRYNINE and WILLIAM R. JUDD. Pp. 730; pl. 480; tables 27. McGraw-Hill Book Company, New York, N. Y. 1957. Price, $10.00.

The jacket of *Principles of Engineering Geology and Geotechnics* proclaims that: "The main purpose of this book is to inform engineers on what they should know about geology and why; and to provide geologists and other specialists of the earth sciences with a knowledge of those phases of civil engineering necessary for their work with engineers."

This is a refreshing approach.[1] Most books on engineering geology are written for engineers and give too much theoretical geology for the engineer and not enough engineering for the geologist. Those books prepared for use of geologists tend to give moral lectures on how important we are to the engineering profession and then to degenerate into long recitals of case histories showing how we saved or could have saved the engineers from disaster. Krynine and Judd have avoided both of these pitfalls.

The first two chapters discuss "Rocks and Minerals" and "Engineering Proper-

[1] The views expressed here are those of the author and not those of the International Cooperation Administration.

ties of Rocks" in a practical manner and in terms understandable to the engineer. The second subject will also considerably enlighten the normal university trained geologist in his own field. Historical geology, paleontology, and geomorphology are discussed only briefly to the benefit of the book. These subjects are also slanted to the practical needs of the non-geological reader.

Nor is this new approach the only refreshing thing in this volume. The illustrations are mostly original and well selected; the reader will miss the same tired old photographs and drawings which seem to come from the files of the Powell and Hayden surveys.

"Formation and Engineering Use of Soils" and "Elements of Soils Mechanics" are discussed simply and in terms understandable by the beginning engineering geologist. Most chapters discussing particular types of structures describe engineering concepts and foundation principles which the geologist in the past had to learn for himself on the job.

The last two chapters are particularly interesting in that they treat subjects of "Earthquakes and Aseismic Designs" and "Some Legal Aspects of Geotechnics." The treatment is all too brief in both instances. Nevertheless, to the reviewer's knowledge, this is the first instance of practical treatment of these subjects in a general engineering geology text.

These unique treatments are combined with wide scope of treatment of conventional engineering geology subjects to form a book of unusual breadth. Virtually every subject to be encountered by the engineering geologist or by a foundation engineer (pertaining to geology and soils) is mentioned. Unfortunately, it is this very breadth of treatment which leads to the book's greatest fault. Most subjects are treated all too briefly. Many subjects are introduced and dropped with little or no explanation of their significance or criteria for recognizing a problem when encountered. A few examples, of many that exist, will serve to illustrate this point.

The chapter on soils mechanics describes the basic concepts, the most common laboratory tests, and the Bureau of Public Roads and Unified Soil Classification systems of soils classification. It does not, however, give enough information to enable one to perform any field or laboratory test himself or even to interpret a test. The description of field tests for the U.S.C. classification system is so sketchy that no one could use it.

There is very little discussion of usefulness or limitations of various soils types for different construction purposes or foundation conditions. These are items that should be understood by any novice.

Thirty-one sentences connect the work "limestone" with dams or reservoirs. Aside from 7 sentences describing Austin Dam (not really a limestone problem) only 10 sentences, in three widely separated places, can be said to attempt to discuss the problems of reservoir and foundation leakage through limestone and exploration and treatment problems in these circumstances.

The extremely useful exploration method of large-diameter calyx drilling is covered in one paragraph describing the equipment and drilling methods. Nothing is said about the usefulness or interpretation of data obtained from calyx holes. The subject of water-pressure tests is similarly treated (1 page). The reader is informed that they are important, that certain precautions are necessary but is told nothing about how to use the tests to appraise leakage possibilities or probable grouting difficulties.

The entire subject of Geophysical Exploration is covered in slightly over 7 pages, of which 2 are illustrations. Electrical and radioactivity logging are discussed separately in 2½ pages.

The process of drainage by electromosis which is interesting but of limited usefulness is treated in 2½ pages, while the entire scope of one of the greatest engineering and geological problems facing us; namely, agricultural drainage, is covered in 1¼ pages.

The subject of masonry dams is especially poorly covered. Dams are classified and explained well. Appurtenant structures are discussed briefly. Problems connected with dams such as sliding, uplift, leakage are also covered briefly. Exploration methods are treated very sketchily (although covered in part under other headings). Principles of exploration during the preconstruction stage are dismissed in three short paragraphs. The manifold duties of a geologist, treatment problems, and reporting during construction of a large dam are treated in only 5 *paragraphs!* (Not including a description of exploration of Kortes Dam—which appears to the reviewer to be rather extraneous.) This type of treatment is particularly unfortunate in view of the generally thorough treatment of tunnels and permafrost, for example, in some other chapters.

Principles of Engineering Geology and Geotechnics is in no sense a handbook. It might be termed a textbook but even in this sense it often treats a subject too briefly for adequate comprehension of its importance or usefulness. The reader is seldom carried to the point where he could even recognize a serious problem. He is never given enough information so that he could understand test results, foundation excavations, or tunnel plans sufficiently to answer the question "Is it good?"

Nevertheless, virtually every subject the engineer and geologist have in common is touched upon. The book thus serves the novice as an excellent check list of possibilities open to him, and the bibliographies at the end of each chapter give leads for further study. The volume is an excellent general reference for the beginner or for the man who wishes to broaden his background.

Krynine and Judd have done a particularly good job of explaining some of the practical applications of geology that the geology student seldom learns in a university. Their book takes the recent graduate or student a long way on the road to learning engineering terminology and concepts.

The authors must have been faced with a serious condensation problem in the preparation of this book. Two volumes would be required to overcome the criticisms offered herein. In spite of its shortcomings, the reviewer believes that this is the most comprehensive book on engineering geology yet published in English. Its approach is new and has long been needed.

JOHN W. FRINK

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INTERNATIONAL COOPERATION ADMINISTRATION,
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Nov. 22, 1957

Atomic Energy in Agriculture. By WILLIAM E. DICK. Pp. 150; figs. 14; pl. 15. Philosophical Library, New York, 1957. Price, $6.00.

In this little book of 6 chapters, the author tells how atomic energy can speed up plant breeding and give new varieties of plants. Also, how it can control pests, and perhaps be used in the future for the preservation or sterilization of foods and drugs. His chapter headings are: 1) Remaking Crop Plants with Radiation; 2) Photosynthesis: Tracing the path of carbon with radio-isotopes; 3) The Path of the Other Elements; 4) Radioactive Materials in the Fight Against Pests; 5) Radioactive Tracers and Forestry; 6) Atomic Radiation and Food Preservation.

His illustrations show a plant of peanuts grown from treated seed that is one-third larger than a plant grown from untreated seed; a piece of irradiated cheese that is quite fresh compared with a mouldy cheese, both of which were wrapped and stored for a year; and two potatoes stored under commercial conditions, the irradiated one fresh and the untreated one shrunken and sprouting. Many new types of hardy plants were produced by irradiation.

Contribution à l'Etude Geologique et Mineralogique de Quelques Gisements de Kaolin Bretons. By J. NICOLAS. Pp. 251; figs. 48; pls. 10. Mémoires de la Société Française de Céramique, Paris, 1957.

This memoir is a supplement to the Society's Bulletin No. 34, January–March, 1957. It is a careful and thoughtful study of the clay deposits of Brittany, which have yielded world-famous ceramics. Its seven chapters deal with the structures of clay minerals; their synthesis, the genesis of the deposits, methods of study, and the deposits of Plémet, Ploemeur and Châteaubriant. To the first two the author ascribes a hydrothermal origin at temperatures from 100 to 200° C; the last is considered to have originated by weathering processes. The memoir is a real contribution to our knowledge of the occurrence and origin of kaolin deposits, and their associated minerals.

Geological Exploration. (Edited by A. K. SNELGROVE.) Pp. 109; figs. 35. Institute of Lake Superior Geology, Michigan College of Mining and Technology Press, Houghton, 1957. Price, $2.00.

This lithoprinted volume consists of 15 brief papers presented at the Institute of Lake Superior Geology held at Houghton, Michigan, May 11–12, 1956. The papers relate to geology and exploration on both the American and Canadian sides of Lake Superior by authors who are or have recently been working in that region. The contents include papers on the native copper district, White Pine mine, Manitouwadge and Blind River deposits in Ontario, magnetic prospecting, relation of gravity to structure in Michigan, geologic factors affecting beneficiation of iron ores in Michigan and at Michipicoten, Ontario, diagenesis, metamorphism and oxidation of Marquette ores, trace elements in soil fractions, geochemical exploration, photogeology, and modern techniques of photogeology and photogrammetry in natural resource development.

There is brought together much regional and general geology of mineral deposits in the Lake Superior region. The two papers on the copper deposits of Michigan and the two on the Uranium deposits of Ontario are of particular interest to economic geologists, as are also the papers dealing with the relation of geological features to the beneficiation of iron ores.

Uranium in South Africa 1946–1956. A Joint Symposium. Vol. I, 546 pp.; Vol. II, 483 pp. The Associated Scientific and Technical Societies of South Africa, Johannesburg, South Africa, 1957.

These interesting volumes have been arranged by the following Five Constituent Societies of the Associated Scientific and Technical Societies of South Africa, namely, the Chemical Institute, the Geological Society, the Institute of Mining and Metallurgy, the Institution of Mechanical Engineers, and the Institution of Chemical Engineers, all of South Africa. There are 30 articles contributed by 33 authors, and a Foreword and Introduction. All but 4 of the articles have been previously published in various South African Journals. Nearly all of the articles

pertain to extraction methods such as flotation, ion exchange, leaching processes, plant construction, materials of the plants, controls, chemistry of products, assaying and evaluation, and plant maintenance. Six of the articles deal with other features, namely, an historical review, origin of the uranium and of the deposits, geological background of the industry, a mineralogical approach to extraction processes, supply of uranium requirements, and natural aspects of the uranium industry.

The historical review by Professor L. Taverner leads one through the stages of discovery and identification in 1923, the underground checking by Weston Bourret in 1944, the Geiger counter checking by G. W. Bain and C. F. Davidson in 1945, the sampling, the laboratory testing by Professor Gaudin at M.I.T., the testing in Canada, the pilot plant work, the negotiations with the U. S. Atomic Energy Commission, and finally, the construction of plants to treat 20 million tons of ore per year.

In his paper on the Occurrence and Origin of Gold and Radioactive Minerals in the Witwatersrand, Dr. W. R. Liebenberg (1956) concludes that the uraninite originally was in detrital grains, which were altered to secondary uraninite and thucholite. The latter is considered to have originated through replacement of detrital uraninite by hydrocarbons. He concludes that since the gold and uranium are contemporaneous, and the uraninite is detrital, therefore the gold must be detrital. The evidence does not seem convincing that the uraninite is detrital.

In the Geological Background of the Uranium Industry, Brock, Nel, and Visser summarize the geology of the Witwatersrand reefs. They discuss the origin of the conglomerates, the gold, and the uraninite, and present the arguments favoring a sedimentary vs. epigenetic origin for the gold and uranium. They believe in a modified placer hypothesis for these minerals, but no satisfactory explanation is advanced for the large amount of sulfur tied up in the pyrite.

In the paper on a Mineralogical Approach to the Development of the Uranium Extraction Processes, W. R. Liebenberg (1956) states that most of the uranium is present as both primary and secondary uraninite developed from the primary, and lesser amounts in thucholite. He shows the distribution of the uranium constituents in the products of gravity, flotation, and electromagnetic treatment of the heads. The constituents are pictured in many fine photomicrographs.

D. H. Stuart, in The Supply of the Raw Material Requirements of the Uranium Program, discusses the supply of the various materials, such as glue, sulfuric acid, manganese oxides, ion exchange resins, etc., required for the program. Mr. R. B. Hagart analyzes the probable uses and world demands for uranium oxide and considers the effect upon the economy of South Africa.

The two volumes give as complete a picture as may be expected of the entire uranium background and industry in South Africa. One cannot but be impressed with the rapid strides that have taken place so successfully in winning such small original quantities of uranium from such large tonnages of ore. The volumes will prove to be a handy reference work for all interested in uranium.

ALAN M. BATEMAN

Geography in the 20th Century, 3rd Edit. Edited by GRIFFITH TAYLOR. Pp. 674; figs. 57; pls. 15. Philosophical Library, New York and London, 1957. Price, $10.00.

The first edition of this book appeared in 1951. It was reprinted in 1953 with minor corrections and revisions and the addition of two new chapters. The present edition adds one new chapter, and chapter 13 has been enlarged and brought up

to date. Twenty-two authors from five countries participate. The volume of 29 chapters is divided into 3 parts: Part I, Evolution of Geography and Its Philosophical Basis; Part II, The Environment as a Factor; and Part III, Special Fields of Geography. The new chapter in the present edition is The Relations of Geography and History, by Professor H. C. Darby of England.

The various chapters cover the history of geography in the 19th century and schools of geography of France, Germany, and among West Slav geographers. The following chapters deal with various geographic areas and the broader geographic features and problems presented in the previous editions.

The book is well balanced and covers most of the problems and broad features of geography.

BOOKS RECEIVED

JAMES M. ALLEN AND JOHN W. SALISBURY

Genetic Relation of Mineralization with Granitoid Intrusives. K. M. Abdullaev. Pp. 294; figs. 68. Moscow, 1954. (In Russian.)

Les Recherches Géophysiques et Géologiques et les Travaux de Sondage dans la Cuvette Congolaise. P. Évrard. Pp. 62; figs. 7. Belgian Royal Academy of Colonial Sciences, Tome VII, Fasc. 1, Brussels, 1957.

Report on the Geological Survey Department for the Year 1956. Pp. 31; fig. 1. Price, 50 cts. Georgetown, British Guiana, 1957. *Activities of the Survey Department during 1956. Several short papers on areal geology.*

Notice Explicative sur la Feuille Douala-Est. G. Weecksteen. Pp. 35; pl. 1; fig. 1. Publications de la Direction des Mines et de la Géologie du Cameroun. Paris, 1957. *Geologic map, scale 1:500,000.*

Bulletin de la Société Géologique de France, Tome 7, Fasc. 1–3. Pp. 279; pls. 26; figs. 39. Price, 1,000 fr. Paris, 1957. *Twenty-four articles in all fields.*

Senckenbergiana Lethaea. W. Struve. Pp. 264; pls. 17; figs. 15; tbls. 2. Wissenschafliche Mitteilungen der Senckenbergischen Naturforschenden Gesellschaft, Band 38, No. 3/4, Frankfurt am Main, 1957.

Report of the Director of the Ghana Geological Survey for the Year 1955–56. D. A. Bates. Pp. 13; tbls. 10. Price, 2 sh. Accra, 1957.

Geology of the Country Around Sheffield. R. A. Eden, I. P. Stevenson, and Wilfrid Edwards. Pp. 238; pls. 6; figs. 30; tbls. 8. Price, £1 7s. 6d. Memoirs of the Geological Survey of Great Britain (to accompany one-inch geological sheet 100, new series), London, 1957. *Complete re-survey of the area, which is nearly all within the Yorkshire and East Midlands Coalfield, renders earlier partial surveys obsolete.*

The Problem of Sampling Mineral Deposits. Filippo Falini. Pp. 61; figs. 18. L'Industria Mineraria, Rome, 1956. *Application of modern statistical methods to the sampling of ore bodies.*

The Mining Laws for the Portuguese East Africa (Moçambique). Pp. 111. República Portuguesa, Província de Moçambique, Lourenço Marques, 1957. *Rules and regulations concerning prospecting, developing and mining in Mozambique.*

Geologie des Ida ou Zal (Maroc). G. de Koning. Pp. 207; figs. 87; maps 4. Leiden, 1957. *Stratigraphy, structure, petrology and economic geology of an area in the high Atlas Mountains of Morocco.*

The Composition and Origin of the Antrim Laterites and Bauxites. V. A. EYLES. Pp. 90; pls. 2; tbls. 10. Memoirs of the Geological Survey of Northern Ireland, Belfast, 1952. *Irish bauxites, which are essentially gibberite bauxites, were formed by de-silication of previously kaolinized basalt and rhyolite.*

On the Presence of Minerals of the Linnaeite Series in Some Copper Ores from the Raipas Formation of Northern Norway. F. M. VOKES. Pp. 112–120; pl. 1. Norges Geologiske Undersøkelse, Nr. 200, Oslo, 1957. *Properties, chemical compositions, and modes of occurrence of siegenite and carrollite.*

Boletin de la Universidad Nacional de Ingenieria, Tomo XXX, Serie IV. Pp. 62. Lima, Peru, 1957.

Coal in Southern Africa. E. P. PLUMSTEAD. Pp. 24; pl. 1; figs. 39; tbls. 3. Price, 4/–. Witwatersrand University Press, Johannesburg, 1957. *Includes discussion on origin, chemistry of formation, classification, distribution, production, and reserves. Chapter on biographical stage of coal formation contains interesting comments on Continental Drift.*

The Geology of the Country Between Belingwe and West Nicholson. B. G. WORST. Pp. 218; pls. 25; figs. 4. Southern Rhodesia Geological Survey Bulletin No. 43, Salisbury, 1956. *The Belingwe District was formerly known principally as a gold mining area, but in recent years the gold output has declined greatly and asbestos has become the chief mineral produced. Chrome has been mined from time to time near the southern end of the Great Dyke, and thre are important deposits of limestone close to the new Lourenço Marques railway. Geologic map, scale 1:100,000.*

Bulletin Number 9 of the Geological Survey of Taiwan. Pp. 136; pls. 2; figs. 3; tbls. 10. Taiwan Geological Survey, Taipei, China, 1956. *Two articles on the coal deposits of Taiwan with English translations. Reserves given. Two geologic maps, scales 1:25,000 and 1:20,000.*

Bulletin Number 2 of the Academy of Sciences of the U.S.S.R. Geophysics Series. Pp. 159. Ann. Subscr., $25.00 (12 issues). Pergamon Press, New York, 1957. *Papers on seismic investigations, rock behaviour under torsion, endured polarization in sedimentary rocks, electrical and magnetic prospecting, and meteorology.*

Electric Smelting of Cuban Serpentine and Laterite Nickel Ores. W. E. ANABLE and L. H. BANNING. Pp. 24; figs. 4; tbls. 18. U. S. Bureau of Mines Report of Investigations 5,346, Washington, D. C., 1957. *Smelting tests indicated that nickel and cobalt cannot be separated effectively by selective reduction techniques. (Nickel-cobalt ratio 36:1.) Dry screening before smelting, however, produced a nickel-cobalt ratio of 80:1.*

Annual Report of the Director of the Geophysical Laboratory 1956–1957. Pp. 151–252, figs. 67; tbls. 25. Carnegie Institution of Washington Year Book 56, Washington, D. C., 1957.

Bureau of Mineral Resources, Geology and Geophysics—Australia, 1957.

Rept. 13. The Geology of Dampier Peninsula, Western Australia. R. O. BRUNNSCHWEILER. Pp. 17; pls. 7; tbls. 2. *Stratigraphy, structure, paleontology of an area in northwestern Australia underlain by marine sediments of Jurassic to Middle Cretaceous age.*

Rept. 33. The Tuluman Volcano, St. Andrew Strait, Admiralty Islands. M. A. REYNOLDS and J. G. BEST. Pp. 38; pls. 18. *Description of volcanism during the formation and subsequent to the formation of the volcanic Tuluman Islands.*

Bull. 34. Permian Bryozoa from the Fitzroy Basin, Western Australia. JOAN CROCKFORD. Pp. 134; pls. 22; figs. 13. *Seventy-nine species are recorded. Forty-two are new species; and three new genera and a new family have been erected in the Cyclostomata.*

University of California Publications in Geological Sciences—Berkeley, 1957.

Vol. 30, No. 5. Geology of a Part of the Manly Peak Quadrangle, Southern Panamint Range, California. B. K. JOHNSON. Pp. 353–424; pls. 7; figs. 8. Price, $1.50. *Geologic map, scale approx. 1:52,200.*

Vol. 30, No. 6. The Cretaceous Gastropod Genus Biplica. Its Evolution and Biostratigraphic Significance. W. P. POPENOE. Pp. 425–454; pls. 2; figs. 2. Price, $1.00. *The new genus Biplica is proposed and described to include opisthobranch gastropods usually referred to Cinulia obliqua Gabb or Oligoptycha obliqua (Gabb). Five species of Biplica are described, of which four are new.*

Vol. 32, No. 5. Hystricomorph Rodents from the Late Miocene of Colombia, South America. R. W. FIELDS. Pp. 273–404; pl. 1; figs. 35; tbls. 7. Price, $2.50. *The La Venta fauna is late Miocene in age, and is correlated with the Carmen de Apicalá and Friasian faunas.*

Illinois Geological Survey—Urbana, 1957.

Circ. 240. Comparison of Methods for Determination of Volatile Matter and Ash in Coal. O. W. REES, F. A. COOLICAN, and E. D. PIERRON. Pp. 8; figs. 2; tbls. 4. *The slower the heating, the lower the indicated volatile matter. Rapid heating of pyrite- and calcite-rich coals gives high ash values.*

Circ. 241. Variation in Coal Reflectance. RAYMOND SIEVER. Pp. 11; figs. 6; tbl. 1.

Circ. 242. Fluid Flow in Petroleum Reservoirs. II. Predicted Effects of Sand Consolidation. WALTER ROSE. Pp. 14; figs. 3; tbls. 3. *Discussion of the Kozeny theory of fluid flow in porous media.*

Circ. 243. Trace Elements in Illinois Pennsylvanian Limestones. M. E. OSTROM. Pp. 34; figs. 4; tbls. 5. *Limestone analyses for agricultural purposes.*

Circ. 244. Brine Disposal in Illinois Oil Fields. A. H. BELL. Pp. 12; figs. 2; tbls. 3. *Twice as much brine as oil produced. Brine pumped into specially drilled wells, dry holes or abandoned wells.*

Circ. 245. Petrography and Origin of Illinois Nodular Cherts. D. L. BIGGS. Pp. 25; pls. 2; tbl. 1. *Chert formed during diagenesis by metasomatic replacement by silica deposited with, and dispersed through, the host rocks.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1957.

Rept. 172–173. Upper Cretaceous Foraminifera from the Rumoi Coal Field, Hokkaidō, Japan. OSAMU FUKUTA. Pp. 17; pl. 1; fig. 1; tbls. 2. *Thirty forms detected—two of them new. Fauna correlates with that of the Navarro or Taylor of the Gulf Coastal Region of the United States.*

On the Myophorians from the Miharai-yama Group in Hyōgo Prefecture. NOBUKAZU KAMBE. Pp. 18; pl. 1; figs. 10; tbl. 1. *Description of Triassic pelecypods of Japan.*

Rept. 175. Variation in Crystal Habit of Pyrite. ICHIRO SUNAGAWA. Pp. 41; pls. 10; figs. 14; tbls. 10. *Habit variations are due to variations of layer growth in different crystallization environments.*

Explanatory Text of the Geological Map of Japan. Nachi (Kyoto-107). ATSUYUKI MIZUNO. Pp. 40; pl. 1; figs. 27; tbl. 1. *English abstract. Geologic map, scale 1: 50,000.*

Coal fields of Japan. Map, 1: 200,000.

Quaternary Mineralization of Japan. Map, 1: 200,000. *Map showing quaternary geology and location of sulphur, limonite, manganese, lateritic nickel, placer and phosphorite deposits.*

Ontario Department of Mines—Toronto, 1957.

Sixty-Fifth Annual Rept. Vol. LXV, Pt. 5, 1956. Geology of Hislop Township. V. K. PREST. Pp. 51; pls. 9; figs. 8; tbl. 1; maps 4.

Sixty-Fifth Annual Rept. Vol. LXV, Pt. 6, 1956. Radioactive Mineral Occurrences in the Bancroft Area. J. SATTERLY. Pp. 176; pls. 26; figs. 23 (incl. maps). *Location, distribution, geologic setting, mineralogy, structure of U-Th deposits in pegmatites, granites, veins, carbonatites. Ore value in excess of $140,000,000. Excellent discussion of origin and mineralogy.*

Quebec Department of Mines—Quebec, 1957.

Geological Rept. 69. Coaticook-Malvina Area. Electoral Districts of Stanstead and Compton. H. C. COOKE. Pp. 37; pl. 1; figs. 7; tbl. 1. *Geologic map, scale 1 mile to 1 inch. Report in English.*

Geological Rept. 72. Southwest Part of Lesueur Township. Electoral District of Abitibi-East. R. BRUCE GRAHAM. Pp. 27; pls. 3; fig. 1; tbl. 1. *Gold, silver, lead and zinc found in agglomerate, in compact "brittle" tuff, and to a lesser extent in fine grained basalt of rhyolitic appearance. Mineralization associated with minor faults near intrusive bosses in the host rock. Geologic map, scale 1,000 feet to 1 inch. Report in English.*

Rapport Géologique 73. Région du Lac Beetz. District Électoral de Saguenay. PAUL-E. GRENIER. Pp. 88; pls. 18; tbls. 2. Two geologic maps, scales 1 mile to 1 inch and 6 miles to 1 inch. Report in French.

Rapport Géologique 74. Région de Johan Beetz. District Électoral de Saguenay. G. E. COOPER. Pp. 57; pls. 8; tbls. 3. *Geologic map, scale 1 mile to 1 inch. Report in French.*

Tanganyika Geological Survey—Dar es Salaam, 1957.

Records of the Geological Survey of Tanganyika. Vol. III, 1956. Pp. 103. Price, 15 sh. *Twenty-one papers dealing with varied aspects of Tanganyika geology; many maps and sections.*

Annual Report of the Geological Survey Department 1956. Pp. 20. Price, 3 sh. *Favorable indications of radio-active minerals have led to increased activity by several mining concerns. BP-Shell group still searches for oil in the coastal belt. Five separate geologic maps included: Nzega-South B36/D1; Lihuhu-South C36/X11 and part of XIV; Lukanga-South C37/B1; Songea-South C36/R1V, and Mwambiti-South B36/D11. Map scales, 1: 125,000.*

U. S. Geological Survey—Washington, D. C., 1957.

Prof. Paper 280-B-D. Geology of Saipan Mariana Islands. Pt. 2. Petrology and Soils. R. G. SCHMIDT, J. H. JOHNSON, and R. J. MCCRACKEN. Pp. 127–207; pls. 14; figs. 25; tbls. 17. *Chap. B—A study of the physical and chemical characteristics of the volcanic rocks of Saipan, their relation to rocks of adjoining regions, and their origin. Chap. C—A study of the composition, organic con-*

stituents, and relative importance of the limestones of Saipan. Chap. D—Classification of Saipan soils, their distribution, extent, genesis, and morphology.

Prof. Paper 280-E-J. Geology of Saipan Mariana Islands. Pt. 3. Paleontology. J. H. JOHNSON, M. N. BRAMLETTE, W. R. REIDEL, and others. Pp. 209–364; pls. 73; tbls. 18. *Six chapters cover calcareous algae, Discoaster and some related microfossils, Eocene radiocolaria, smaller foraminifera, larger foraminifera, and echinoids.*

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Prof. Paper 303-A, B. The Paleozoic Section in the Shainin Lake Area, Central Brooks Range, Alaska. A. L. BOWSHER and J. T. DUTRO, JR.
A New Upper Paleozoic Formation, Central Brooks Range, Alaska. W. W. PATTON, JR. Pp. 45; pls. 6; figs. 6. *Type sections of five new formations of Paleozoic age.*

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SCIENTIFIC NOTES AND NEWS

THE AMERICAN CONGRESS ON SURVEYING AND MAPPING will hold their Annual Meeting, March 23–26, to be followed directly by that of the American Society of Photogrammetry, March 26–29, with a co-exhibit, at the Shoreham Hotel, Washington, D. C.

DR. M. S. KRISHNAN, former Director of the Geological Survey of India, is now the Director of the Indian School of Mines and Applied Geology, Dhanbad, India.

VINTON H. CLARKE has resigned as vice president in charge of mining and exploration of Howe Sound Company and will join the mining, geological and metallurgical consulting firm of Behre, Dolbear & Co., Inc., New York City.

HERBERT E. HAWKES, previously with the Department of Geology and Geophysics at the Massachusetts Institute of Technology, has been appointed Professor of Mineral Exploration in the Division of Mineral Technology, University of California, Berkeley.

The Sociedade Brasileira de Geologia at its annual meeting in November elected OLOF ÖDMAN, BORIS CHOUBERT and W. D. JOHNSTON, JR., Corresponding Members.

VINCENT C. KELLEY, on leave from the University of New Mexico, will be visiting professor at Columbia University during the spring of 1958, where he will teach graduate courses in structural geology.

ELLIOT GILLERMAN is now Associate Professor of Geology at the University of Kansas. He was formerly on the staff at the University of Texas.

S. E. MALOUF has left Chibougamau for Toronto where he will assume his duties as vice president and general manager of Chibougamau Mining and Smelting. Dr. Malouf is consulting geologist for Campbell Chibougamau and also for Yorcan.

W. A. HUTCHISON has been appointed general manager of Phelps Dodge Corp. of Canada, Ltd., the newly-formed Canadian exploration subsidiary of Phelps Dodge Corp. of New York.

PAUL D. FOOTE, retired vice president of Gulf Oil Corp. in charge of research and development, has received an interim appointment from President Eisenhower to be Assistant Secretary of Defense for Research and Engineering.

RICHARD P. GOLDTHWAIT, Professor of Geology at Ohio State University, has been on leave to study glaciers and glacial deposits in New Zealand under a Fulbright grant.

J. AUSTEN BANCROFT, consulting geologist for the Anglo-American Corporation of South Africa and formerly Professor of Geology at McGill University, died on December 11th in Johannesburg at the age of seventy-six.

RAYMOND C. LINDLOF has accepted a position as chief engineer and geologist for Federal Uranium Corp. in Salt Lake City, Utah.

CARLETON SAVAGE, economic geologist, and RICHARD S. KOPP, minerals analyst, have joined the staff of the Idaho Bureau of Mines and Geology. Dr. Savage was formerly associate professor of geology at the Kent State University in Ohio, and Mr. Kopp was previously associated with the United States Geological Survey in Nevada.

C. P. FINLAYSON, geologist, formerly with the American Smelting & Refining Co. has accepted a position with the Tennessee Geologic Survey with offices in Knoxville.

WILLIAM W. STALEY of the University of Idaho at Moscow, Idaho, has returned to this country after spending a year's leave of absence in Korea, helping to set up a modern engineering program at the Seoul National University.

AARO E. AHO has started a geological consulting practice at 4219 Lions Avenue, North Vancouver, B. C., Canada.

PARKE A. HODGES, vice president of Behre Dolbear & Co., Inc., mining geological and metallurgical consultants of New York, has been in Sweden, Liberia and Nigeria on professional work.

R. G. LINDLOF has been appointed chief engineer and geologist of Federal Uranium Corp. He was for the preceding four years geological engineer with the Atomic Energy Commission in Casper, Wyoming.

HAROLD S. HICKS, chief geologist at Steep Rock Iron Mines, Ltd., has been made superintendent of the company's new concentration plant.

H. L. YOUNG, vice president of American Zinc, Lead & Smelting Co., has been elected to the board of directors to fill the vacancy caused by the recent death of Mr. Erle V. Daveler, who was a director and vice president.

G. VIBERT DOUGLAS has moved to 40 Sherbourne Street, North, Toronto 5, Ontario, where he is now carrying on consulting work.

S. G. LASKY, Staff Assistant for Minerals in the Office of the Secretary of the Interior, spent the first two weeks of February in Havana as mining and minerals consultant to the Cuban Government in connection with the First National Symposium on the Natural Resources of Cuba.

The Society of Economic Paleontologists and Mineralogists has elected M. A. HANNA of Houston, Texas, C. E. DECKER of Norman, Oklahoma, and H. E. THALMANN of Stanford, California, as honorary members.

GEORGE S. BUCHANAN, Director, Husky Oil Company, Cody, Wyoming, was elected the 42nd president of the American Association of Petroleum Geologists on March 13. The 1958–59 Executive Committee consists of GRAHAM B. MOODY, SHERMAN A. WENGERD, GORDON I. ATWATER, and HAROLD T. MORLEY.

Behre Dolbear & Company announce the appointment of VINTON H CLARKE, formerly Vice President in Charge of Mining, Howe Sound Company, as an associate.

The Atomic Energy Commission announced that United States uranium concentrate production has reached an annual rate of 10,000 tons U_3O_8, and that 11,826 tons U_3O_8 had been imported in 1957, making a total of 21,826 tons. At the beginning of 1957 there were 12 operating mills in the Western U. S. and 4 additional mills came into production during the year.

HATTEN S. YODER, JR. of the Geophysical Laboratory, Washington, D. C., gave a series of lectures on geochemistry at the Department of Geology, University of Minnesota, during the week of January 26, 1958.

GORDON RITTENHOUSE, of the Shell Development Company, Houston, Texas, has been elected president of the Society of Economic Paleontologists and Mineralogists.

The concentration of radioactive strontium-90 in the human body from nuclear explosions rose 33 per cent in the year ended June 30, 1957, but is still well below the maximum permissible concentration, according to LAURENCE KULP, ARTHUR R. SCHULERT, and WALTER R. ECKELMANN. The survey, now in its fifth year, is the most comprehensive world-wide study of the concentration of radioactive fallout in the bone structure of man. It was conducted at the Lamont Geological Observatory under a grant from the Atomic Energy Commission.

AUGUSTUS B. KINZEL has been elected president of the American Institute of Mining, Metallurgical, and Petroleum Engineers.

OLAF P. JENKINS, State Mineralogist and Chief of the California State Division of Mines for eleven years, has retired from that position and will enter private practice as an economic geologist for Carroll E. Bradberry and Associates of Los Altos, a firm of consultants specializing in natural resources. Dr. Jenkins joined the Division of Mines in July 1929 as Chief Geologist of the Geologic Branch. He became State Mineralogist and Chief of the Division in February 1957. In addition to other assignments, Dr. Jenkins will continue his direction of a geologic survey of the 2,300,000-acre ranch holding in Argentina recently purchased by Joseph J. Coney of San Francisco. This survey will be part of the comprehensive report on the property now under preparation by the Los Angeles firm.

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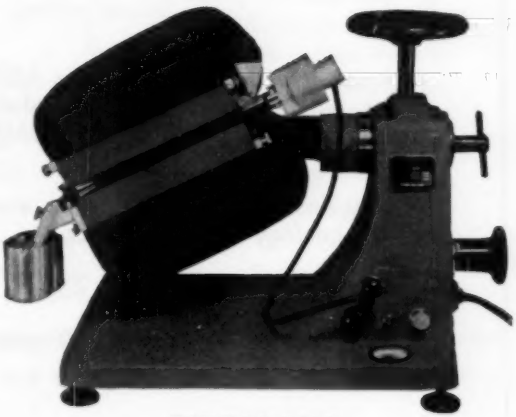

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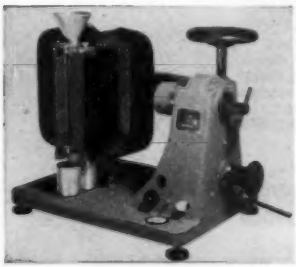

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